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MARINE CHITIN-DECOMPOSING BACTERIA*

By

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Chitin is found in various members of the plant and animal kingdoms. It forms the main skeletal material of the Insecta and Crustacea in the animal kingdom, and is present also in tissues of fungi. Chitin has an elementary composition of $C_{32}H_{54}O_{21}N_6$ (*6*), On hydrolysis with concentrated acid it yields glucosamine and acetic acid in proportions which indicate that there is an acetyl group for each glucosamine residue. It is a tough leathery substance, insoluble in water, in concentrated alkalis, and in the common organic solvents. No essential differences have been found in the chitin from animal and vegetable sources (*4*, *8*).

In the course of a study of the decomposition of chitinous material in natural marine media, a number of bacteria capable of decomposing chitin were isolated from marine sand, mud, and water (*7*). Chitin-decomposing bacteria were isolated also from the intestinal contents of several common marine animals. The following methods were used in the isolation of the bacteria from their respective habitats.

Purified chitin was prepared from horseshoe crab shells according to the procedure of Benton (*2*), and ZoBell and Rittenberg (*11*). The shells were treated successively for prolonged periods with 1 percent hydrochloric acid, 2 percent potassium hydroxide, and 95 percent

* Contribution No. 273, from The Woods Hole Oceanographic Institution, Woods Hole, Mass.

ethyl alcohol. The snowy white material which remained reacted positively to simple qualitative tests for chitin (*3*).

In preparing liquid culture media, 1 by 5 cm. strips of the purified chitin were placed in test tubes, and partly covered with sea water, or with sea water containing additional nutrients (Fig. 12). The medium best suited for the detection of chitin-decomposing bacteria

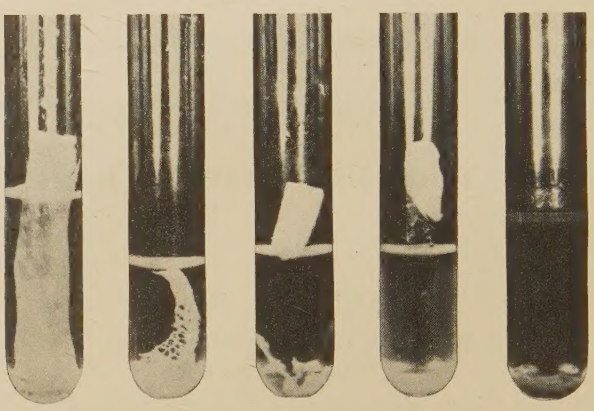

Figure 12. Decomposition of purified chitin in liquid culture medium. The tube on the left is the control; the other tubes show the chitin in various stages of breakdown.

consisted of a strip of chitin in a solution used by Waksman (*10*). This basic medium had the following composition:

glucose	1 gram
peptone	1 gram
K_2HPO_4	0.05 gram
Sea water (filtered)	1000 ml

By elimination and by substitution in this basic medium, the metabolic requirements of the bacteria were studied.

Solid media were prepared from the liquid culture media either by the addition of 15 grams of agar to each liter of solution or by diffusion of the nutrient solutions through silica gels. Where solid media were employed strips of sterile purified chitin were placed on the surface of the hardened gel (Fig. 13). The silica gel plates were prepared under as nearly aseptic conditions as possible; all other media were sterilized by autoclaving for 20 minutes at 120° C.

One additional solid medium was found useful for the rapid detection of chitin-decomposing bacteria. It was prepared by uniformly

dispersing chitin in agar according to the following procedure. Fifteen grams of purified chitin were added to 150 ml. of 1 : 1 sulfuric acid and kept overnight in the refrigerator. The chitin was dissolved by this treatment but analyses showed that it was not hydrolyzed. The following day the chitin was precipitated by the addition of approximately 140 ml. of 20 percent potassium hydroxide. The precipitate was placed on a Büchner funnel and washed repeatedly with distilled water until the filtrate was neutral to litmus. Thirty-five grams of the chitin, as removed from the filter, were then added to the basic liquid

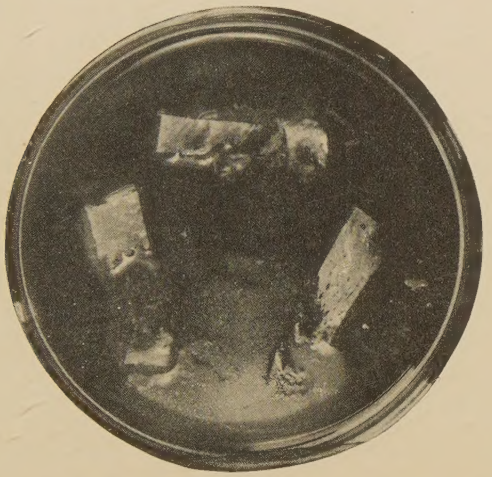

Figure 13. Breakdown of strips of purified chitin on the surface of a silica gel plate inoculated with a sample of marine mud.

medium. After autoclaving, the agar was thoroughly shaken to redistribute the chitin, and Petri plates were poured. In this condition the medium was of a uniform milky-white opacity. When chitin-decomposing bacteria grew on the surface of this agar they dissolved the chitin, thereby producing a clear halo around each colony (Fig. 14). By noting the length of time necessary for the appearance of halos the rates of bacterial activity could be estimated. Bacteria which decomposed chitin rapidly often produced a halo after two days' growth whereas others required eight to ten days for a positive test. Although bacteria which were unable to decompose chitin often grew well on the medium, they did not alter it in appearance (Fig. 14).

The media were inoculated with sea water, marine sand or mud, a piece of decomposing horseshoe crab shell, or with a loopful of ma-

terial from the intestinal tract of a fish or other marine animal. In order to test a given sample for chitin-decomposing bacteria, several different media were inoculated. These were incubated at room temperature and examined periodically for evidence of chitin breakdown. Growth was slow in the medium consisting of only chitin in sea water, whereas the same bacteria decomposed the chitin more rapidly when additional nutrients were present.

In preliminary work cultures of bacteria which showed no evidence of chitin-decomposition were kept one year before being discarded as

Figure 14. Growth of marine bacteria on agar containing precipitated chitin. Upper half inoculated with a pure culture of chitin decomposing bacteria: lower half inoculated with a culture incapable of attacking chitin.

negative. It became evident, however, that several weeks were adequate for detecting the chitin-decomposing capacity of most species. After bacterial development took place a second tube of enriched medium was inoculated with a loopful of material from an original positive culture. Growth from the second tube was then streaked either on nutrient agar plates or on agar medium containing precipitated chitin. In either case the colonies which developed were again retested for their ability to attack chitin. In this way pure cultures of the bacteria were obtained.

Visible dissolution of the chitin, either in liquid medium or on a solid agar surface was indisputable evidence that the chitin was being attacked. To detect incipient decomposition a hand lens was helpful.

During advanced stages of decomposition the shell was frequently observed to be "eaten" away in spots. The liberation of ammonia from media lacking peptone or nitrate, reducing substances from media lacking glucose, or a pronounced change in acidity, were further reliable evidence of chitin-decomposition.

The chitin-decomposing bacteria isolated from the sea were found to be Gram negative, asporogenous, motile rods. Among the readily demonstrable products resulting from the decomposition of purified chitin by pure cultures of the bacteria were ammonia, reducing substances, and organic acids. All of the bacteria liquefied gelatin rapidly, but failed to digest cellulose even after incubation for many weeks. Most of the bacteria were unable to hydrolyze starch: about half of them were able to reduce nitrates, but none were able to produce hydrogen sulfide. Likewise, the various cultures of bacteria differed in their ability to ferment simple sugars and alcohols. Some of the bacteria produced pigments while others did not. They also varied in the rapidity of decomposition of chitin. None of the cultures was able to grow in fresh water media. No attempt was made, however, to acclimate the bacteria by reducing the salt content of the media gradually with each successive transfer.

A description of two types of bacteria, selected as representing the marine chitin-decomposing bacteria isolated in the present investigation, is reported here. Five strains of the first type, *Bacterium chitinophilum* are described. These strains vary in their ability of reducing nitrate and of utilizing several sugars and other carbohydrates, but appear to be sufficiently similar to warrant placing them together as one type. From the description given by Benecke (*1*), his *Bacillus chitinovorous* might be identical with either Strain I, II, or III. Rammelberg (*9*) and Folpmers (*5*) each isolated a bacterium, the former from harbor water, the latter from the soil, which apparently correspond to the one described by Benecke. Benton (*2*) described 17 types of chitin-decomposing bacteria, but was unable to identify any of these with *B. chitinovorous*. Two of her groups, according to the description given, could be identical with Strain I or Strain IV of *B. chitinophilum*. Except for color, Strain IV is identical with one of 14 types described by ZoBell (*11*). *Bacterium chitinochroma*, the second type isolated in this study, is represented by a single strain.

Bacterium chitinophilum, n. sp.

Short rods, .35 to .65 by .95 to 1.5 microns in size. Gram negative. Motile.

Basic agar plate: colonies circular, smooth, entire, raised, white.

TABLE I

Name	*Average Size (microns)*	*Color on Chitin Medium*	*Gram Stain*	*Motility*	*Nitrate Reduction*	*Starch Hydrolysis*	*Gelatin Liquefaction*	*H_2S Production*	*Cellulose Digestion*	*Dextrose*	*Sucrose*	*Lactose*	*Glycerol*	*Mannitol*	*Sources*
Bacterium chitinophilum *Strain I*	0.5 × 1.2	White	−	+	+	−	+	−	−	+	+	−	+	+	Mud, intestines of horseshoe crab and dogfish.
Strain II	0.5 × 1.4	White	−	+	+	−	+	−	−	+	+	+	+	+	Water, mud, intestines of puffer.
Strain III	0.5 × 1.2	White	−	+	+	−	+	−	−	+	+	−	−	−	Water, sand, mud.
Strain IV	0.5 × 1.2	White	−	+	+	−	+	−	−	+	−	−	+	+	Intestines of quahaug and sand crab
Strain V	0.5 × 1.0	White	−	+	−	−	+	−	−	+	+	−	−	+	Mud, water.
Bacterium chitinochroma	0.5 × 1.2	Yellow	−	+	−	+	+	−	−	+	+	−	−	−	Sand, water, intestines of squid.

Basic liquid medium: moderate growth, sometimes with formation of ring or pellicle. Scant granular sediment.

Sea water gelatin: liquefaction, growth absent in stab but abundant in liquefied zone.

Does not hydrolyze starch nor produce hydrogen sulfide. Four of five strains reduce nitrates. The strains vary in their ability to ferment sugars. All are unable to digest cellulose.

Aerobic.

Optimum temperature 20° C.

Habitat: Common in marine sand, mud and water. Also isolated from the shell of a decomposing horseshoe crab, *Limulus polyphemus*, and from the intestinal tract of *Venus mercenaria mercenaria*, *Ovalipes ocellatus ocellatus*, *Mustelus mustelus* and *Spheroides maculatus*.

Bacterium chitinochroma, n. sp.

Short rods, .45 to .75 by .90 to 1.4 microns in size. Gram negative. Motile.

Basic agar plate: colonies circular, smooth, entire, raised, varying in color from lemon to deep orange.

Basic liquid medium: abundant growth with production of pellicle. Scant granular sediment increasing with age of culture.

Sea water gelatin: active liquefaction, no growth in stab, but thick bright yellow growth throughout the liquefied zone.

Does not reduce nitrates: hydrolyzes starch: does not produce hydrogen sulfide, ferments dextrose and sucrose, but not lactose, glycerol and mannitol. Does not digest cellulose.

Aerobic.

Optimum temperature 20° C.

Habitat: marine sand, mud, and water. Also isolated from the intestinal tract of the squid, *Loligo pealeii pealeii*. Common occurrence.

The characteristics of the bacteria are summarized in Table I.

SUMMARY

Bacteria capable of decomposing chitin were isolated from sea water, marine sand and mud, and the intestinal contents of several marine animals.

Two species of marine chitin-decomposing bacteria are described. All of the bacteria are Gram negative, asporogenous, motile, short rods. Ammonia, reducing substances, and organic acids are readily demonstrable products resulting from the decomposition of purified chitin by pure cultures of the bacteria.

These bacteria decompose chitin not only in purified preparations but also in natural chitinous material such as horseshoe crab shell.

The writer is indebted to Dr. S. A. Waksman for suggestions in carrying out the investigation and in preparing the manuscript.

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DEPTH RELATIONSHIPS OF PLANKTON DIATOMS IN SEA WATER*

By

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For more than twenty years I have been directly interested in the space relationships of marine plankton organisms. Not least among the unsolved problems of these relationships is that of the maintenance of residence at appropriate depths by microscopic creatures, e. g., the plankton diatoms. Even the questions concerning the fate of the dead bodies, empty frustules, or other remains of these tiny plants have considerable importance not only for the marine biologist but also for the marine hydrologist, or physicist, or chemist. Such problems are difficult enough if presented in the simplest form for a particular kind of particle of designated shape, density, dimensional limits, frictional characteristics, solubility, etc. They are far more difficult in Nature because of the endless complications and modifications introduced by biological influences of many kinds.

Still, I believe that there exist certain major tendencies of behavior of microscopic particles in respect to maintenance of level or change of levels in natural waters which might be worked out if a well organized program of investigations were carried over a period of time and a wide extent of observable conditions. However, I do not believe that the rate of settling of marine plankton diatoms, or of their frustules (the kinds of small particles most familiar to me) can ever be expressed dependably by a mathematical formula because, at any given point in the sea, sinking may occur according to formula today and not tomorrow, the difference being due to influences added, subtracted, or modified in ways not open to prediction.

While a study of marine deposits shows that plankton diatoms are represented in them, this representation is much less than might be expected from our knowledge of excessive abundances in many seas. The reasons for this condition are probably to be found mainly in the characteristics fitting the plankton forms for a suspended existence and in the influences contributing to their suspension. Consequently, there are interesting relationships between the problems of suspension

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and of deposition as well as between those of suspension and maintenance of life.

There are recorded nearly two hundred species of marine diatoms which seem to spend most of their active existences adrift. For all such it appears that suspension must be an advantage and that they must possess some means of regulating it within necessary limits. For them the primary need is to keep suspended at the levels which are favorable for their growth and development. Confronted with the endless vagaries of waves, currents and other disturbances, this often proves to be impossible. On the other hand, the vast numbers in which these tiny plants appear from time to time in many parts of all oceans show that they have some means for keeping contact with tolerable if not with favorable conditions. Needless to say, these powers of holding an acceptable level add indefinitely to the difficulty of measuring or of describing their powers of suspension and of distinguishing between physical and biological causes of the phenomena of suspension or of deposition in any particular case.

In the discussion of ability to keep adrift considerable stress is rightly given to the production of gases and oils by the living substance. Since the microscopic plant has nearly the same specific gravity as ordinary sea water, it seems to be certain that a slight change in relative volume of either gas or oil would suffice to make the diatom either lighter or heavier, and so capable of shifting position slightly in either the downward or upward direction. Since it is improbable that for any individual diatom this power of adjustment would be worth much in relation to change in level, it seems probable that its value would lie in approximate maintenance at a tolerable or favorable level.

A less changeable feature in relation to suspension is that of structure of the frustules, the walls being thinner and lighter in all floating diatoms and showing highly modified protuberances in many forms. In the genus *Chaetoceros* these protuberances have the shape of delicate hairs many times longer than the main body and so presenting a relatively enormous expanse of surface to delay sinking. Some kinds of plankton diatoms get similar relative expanse of surface by merely lengthening the whole frustule into a thread, without much development of protuberances. Reduction in size of the body would have a similar effect but it is not clear that this would be likely to occur in a way to promote suspension at a favorable level.

Formation of mucous threads or films might be expected to give material aid to suspension by increase of friction over larger and moving surfaces, but since the diatoms of colder seas exhibit these developments more generally, it may be doubted that they have high value in

that way. Still, it may be that they do and that they are more prominent in colder seas because of some coincidental condition.

In some species it seems probable that the extrusion of protoplasmic threads or streams aids in suspension, partly by exerting stream friction against the surrounding water and partly by increase of surface.

If suspension is really promoted by this means it can be more directly controlled than by any of the others mentioned. While, at first, it may seem improbable that the effect of protoplasmic extensions would be great enough to have appreciable effect on suspension, this improbability tends to disappear when one recalls that for the living diatom very little influence is needed to tip the balance of adjustments to favor suspension.

For the sake of clarity most of the foregoing discussion has been written as though the surroundings of marine plankton diatoms were fairly constant, as they are not even at a single chosen depth. Various features in the ordinary relationships of these surroundings may or may not aid in suspension at a favorable level. In many cases suspension is promoted by slight (unobservable) movements of small water masses either horizontal, vertical, or irregular. No trustworthy data exist from which to estimate the importance of this influence but that it must be considerable is indicated by the movements of diffusion and of mixing of minute and microscopic particles often observable in small masses of water and in air. On the other hand, it is still more certain that such movements may carry certain diatoms or certain populations to a lower or higher level or to some lateral point which is less favorable for suspension or maintenance.

Still more indefinite and elusive would be the effects of movements of vigorously swimming animals which must be directly disturbing to suspension of diatoms in any certain relation but which indirectly constitute aid to suspension by changing gaseous and organic content of the water and by promotion of vigor in all functions of the microscopic plant. This indirect effect might include removal of particular diatoms to levels extremely favorable, in which their increasing numbers and more vigorous growth would aid materially in securing suspension although the general alteration of relationships may have been considerable.

Ordinarily conditions of viscosity may be supposed to favor suspension of diatoms which have adjusted themselves to conditions at a particular depth in the sea, because viscosity is understood to increase with increase of pressure and with decrease of heat. But nearly all diatoms are active only at depths less than seventy meters, in all cases

being confined to levels within reach of numerous causes of disturbance of water masses. For such reasons it appears that viscosity does not bear a constant relation to level and that it is subject to considerable variation at different points in any level, depending upon more or less immediate influences of wind, wave, and of bottom topography. The same is true of a number of other physical and chemical conditions which may have possibilities of influence on flotation.

In harmony with the foregoing suggestions it seems fair to assume that in ordinary conditions of all seas there is little tendency for plankton diatoms to settle to the bottom so long as they are in vigorous activity, either photosynthetic or assimilative. It is probable that those forms having heavier and smoother frustules are able to offset their greater tendency to sink by developing some peculiarity in this activity, for example, special formation of oils or frequent division to produce smaller cells.

At any rate, it seems to be certain that most of those tending to deposition are moribund, dead, or otherwise inactive. The more common forms of individual cells in plankton diatoms are smooth discoid, rough or spinose discoid, heavily setose discoid, cylindrical, spindle shaped, and filamentous. Many of them unite into chains so that they behave more or less like filaments. Even when the living matter has disappeared and only the bare frustules are left the chains are often prominent in a plankton catch and they are probably much more prominent in the undisturbed condition in the sea. This is especially true of smaller forms in the genus *Chaetoceros* which often appear in large numbers in the dead or cleaned (empty frustule) condition near the surface of the sea, indicating that sinking may be a long and highly variable process for many plankton diatoms.

Judging from the rate at which diatoms sink through a distance of several centimeters in a container in the laboratory one might conclude that they may sometimes settle from higher to lower levels in the sea at a rate of several meters per day, perhaps as many as twenty or thirty meters. However, no reliable data concerning the rate of sinking exist, not even as to the laboratory differences in rates shown in relation to the different species. Therefore, it seems highly probable that laboratory observations lack dependability as a basis for estimating or understanding the actual rates of sinking in the ocean, just as they do for so many other natural phenomena.

For one thing, the mere increase in viscosity as successive lower levels are reached in descending from the surface in many instances would be sufficient to materially change the rate of sinking, perhaps almost stopping descent below the hundred meter level for delicate frustules. This, together with slight movements of surrounding

water particles might result in an empty frustule remaining afloat for so long that it would disintegrate or redissolve into a colloidal or other state in which its substance would remain suspended without ever being deposited. There seems to be a reasonable probability that this actually happens and that the lack of abundance of plankton forms in marine sediments is due to the ordinary tendency of sea water to reduce their delicate frustules to solution. That is to say, the problem of suspension or of sedimentation is intimately related to the problem of disintegration.

Lest it appear that I have merely succeeded in making the situation seem to be hopeless so far as the study of microscopic particles in the sea is concerned, let me say in conclusion that any addition to reliable information is helpful and important, no matter if it may fall short of full solution of the problems involved. Essential approximations to correct solutions may come later.

THE WATER MASSES OFF THE WEST COAST OF NORTH AMERICA*

By

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In reporting the results of the 1937 cruises of the "Bluefin" off southern California, Sverdrup and Fleming (in press) found that within the limited area which they investigated, two primary water masses were present, mixtures of which made up the water at depths between 200 meters and 400 meters in this region, and they developed a convenient method of using temperature-salinity relationships to study the processes of mixing. The present paper is an extension of the same method to all the waters which border on the west coast of North America from Alaska to Mexico.

A series of temperature-salinity curves from stations located at various points from the Gulf of Alaska to Central America show a regular transition in the character of the water masses from north to south and clearly indicate that the water along the entire coast is a mixture of two extreme water masses. The regions in which these masses lie have been called by Sverdrup, Johnson and Fleming (MS) the Subarctic North Pacific and the Equatorial Pacific regions, respectively. The former extends over the entire North Pacific at latitudes higher than about 43° N. and the latter covers a triangular area over the equatorial region of the Pacific, whose base lies in the western Pacific between about latitudes 20° N. and 15° S. and whose apex lies on the Equator at about longitude 130° E. The region of transition between the Subarctic and Equatorial waters includes that adjacent to the west coast of the United States and Mexico and extends to a distance of 400 to 600 miles or more from the coast. It was within this region of mixing that, in 1939, the "E. W. Scripps" occupied eighty hydrographic stations the locations of which are shown in Figure 15. The area indicated by the dashed line is that covered by the "Bluefin" in 1937. In Figure 16 is presented a series of T-S curves from the outermost stations (VIII 34–VIII 79) of the six station lines. Curves from four stations further to the north are included, those from "Catalyst" station C4843-12819 (48° 43′ N. 128° 19′ W.), "Carnegie"

* Contributions from the Scripps Institution of Oceanography, New Series, No. 141.

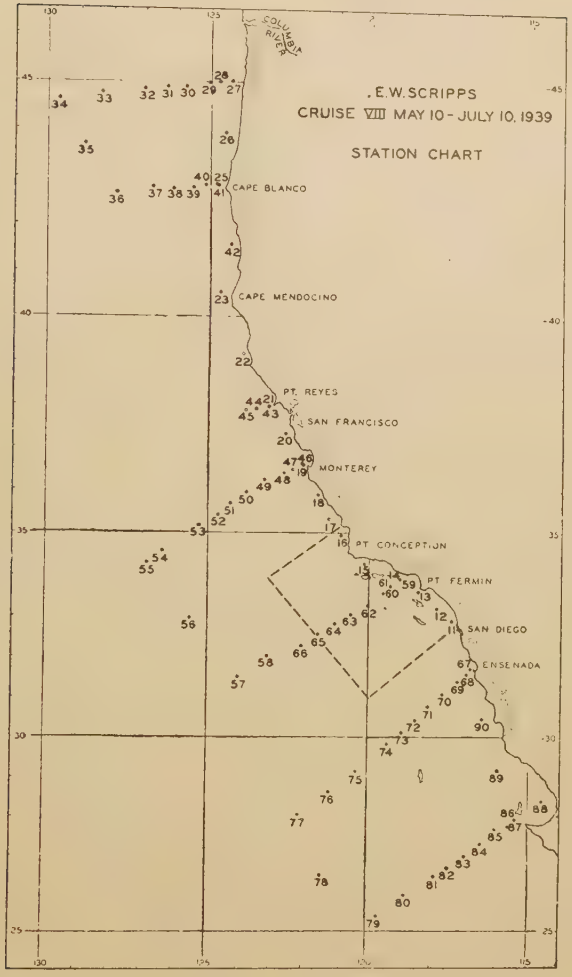

Figure 15. Station Chart, "E. W. Scripps" Cruise VIII.

stations 120 (47° 02′ N. 166° 20′ E.) and 124 (52° 19′ N. 162° 02′ W.) and "Bushnell" station *a*, 1934 (50° 30′ N., 175° 16.5′ W.), and from two stations to the south, "Bushnell" stations 299 and 307, 1939 (19° 02′ N., 86° 50′ W., and 22° 22.5′ N., 111° 25′ W.).

The curve from "Carnegie" station 124 in the eastern part of the Subarctic North Pacific region is similar to those from "Carnegie" station 120 and "Bushnell" station *a* in the western and central parts,

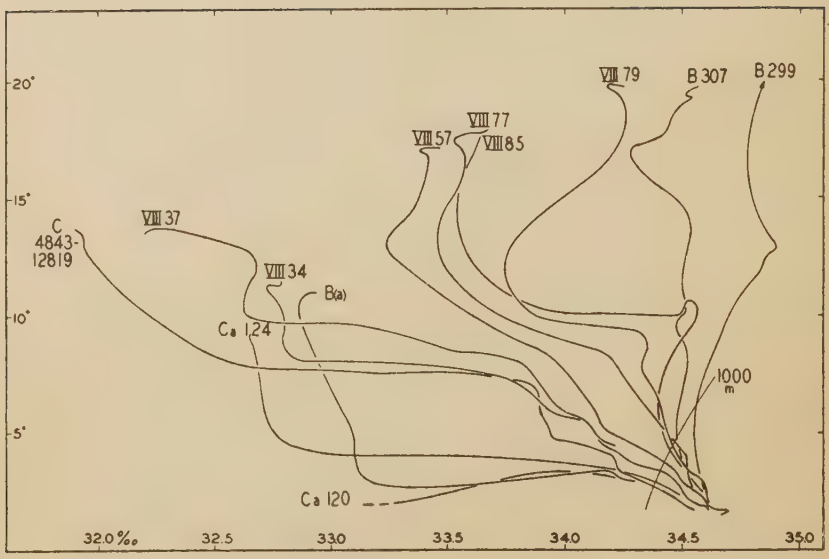

Figure 16. T-S Curves of Stations in the Eastern North Pacific from off the Aleutian Islands to Central America.

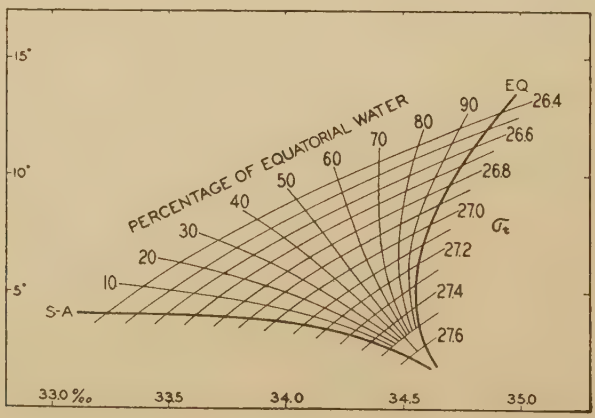

Figure 17. Graph showing T-S curves defining Subarctic North Pacific and Equatorial water, and curves for various percentages of Equatorial water assuming mixing along surfaces of equal σ_t.

and for our purpose is taken as defining the Subarctic water mass. The characteristic T-S curve defining the Equatorial water mass of the northeastern part of the Equatorial Pacific was obtained from "Bushnell" station 299. It is comparable to those from other "Bushnell," "Carnegie" and "Dana" stations in the region (Sverdrup, Johnson and Fleming, MS), and to the curve for Equatorial water derived by Fleming (1939). These characteristic T-S curves defining the Subarctic and Equatorial water masses are entered in Figure 17.

For further analysis it will be assumed that the observed distribution of temperature and salinity in the area of transition is maintained by horizontal flow and by lateral mixing of waters having the T-S relationships defined above, and that mixing takes place primarily along surfaces of equal σ_t. This latter assumption is equivalent to assuming nearly isentropic mixing. One cannot establish strictly isentropic surfaces in the ocean as Rossby (1939) has done for the atmosphere where, in dry air, they correspond to surfaces of equal potential temperature. Surfaces of equal density *in situ* do not fulfill the necessary conditions but those of equal σ_t closely approximate such isentropic surfaces. A body of water cannot be displaced even along a σ_t surface without somewhat altering the distribution of mass, nor will the mixing of two bodies of equal σ_t but of different temperatures and salinities result in a mass of the same σ_t. The departures are, however, small and may in a first approximation be disregarded.

On the assumption that water masses of intermediate character are formed by the mixing along σ_t surfaces of Subarctic and Equatorial waters, it is possible to prepare a diagram (Figure 17) from which the percentage of Equatorial water can be found for water of any observed temperature and salinity. In constructing this diagram, the σ_t lines were drawn between the two limiting T-S curves, SA and EQ, and were divided into the proportional parts from which smooth curves representing the several percentages of Equatorial water were drawn. It must be noted, however, that the determination of percentage composition by this means cannot be used for water above about 100 meters, since near the surface vertical mixing related to the effects of wind and local changes due to absorption of solar radiation, evaporation or precipitation are prominent and any mixing along σ_t surfaces will be more or less completely masked. This is especially true whenever the interval between stations in space or time is great. Below a depth of about 1000 meters the differences in the T-S relationships of the two extreme water masses are so small that application of the method is doubtful.

Figures 18 to 23 are vertical sections along the six station lines of Cruise VIII of the "E. W. Scripps" and were constructed from

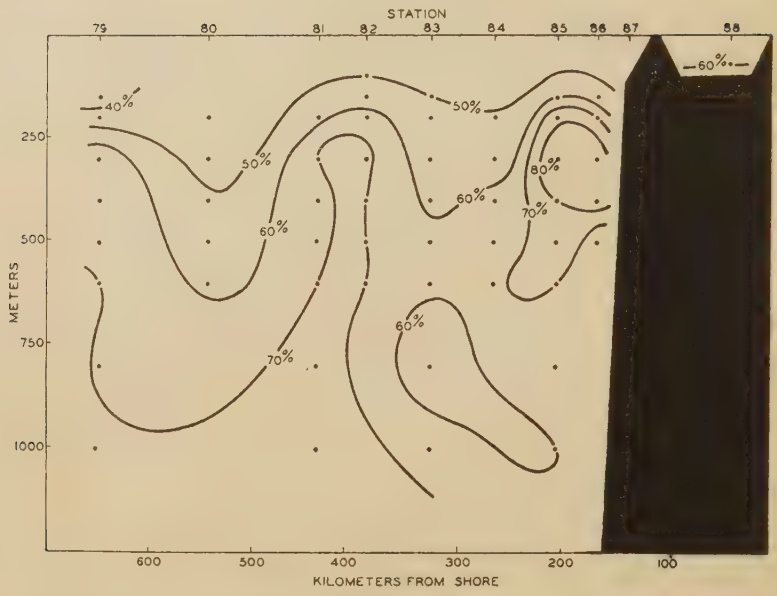

Figure 18. Section 6 off Cedros Island, Lower California, showing percentage of Equatorial water.

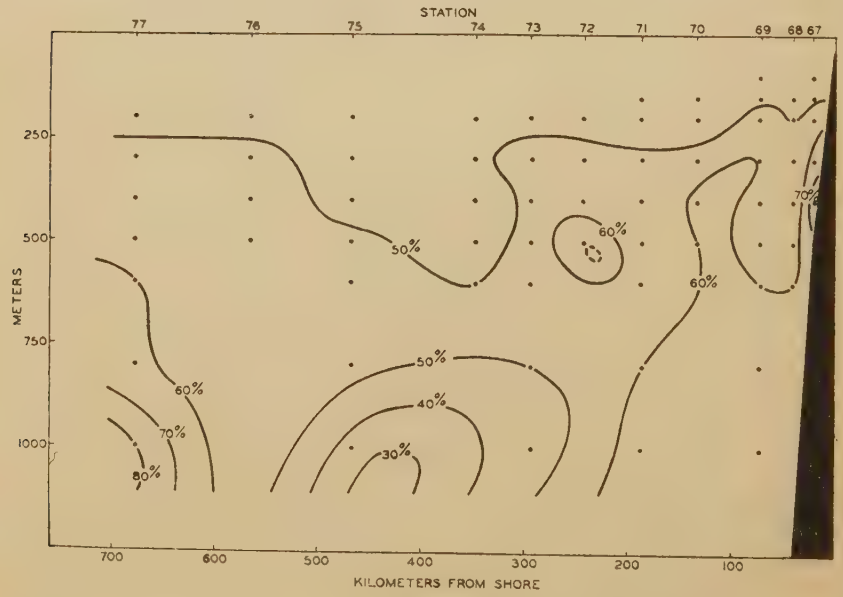

Figure 19. Section 5 off Ensenada, Lower California, showing percentage of Equatorial water.

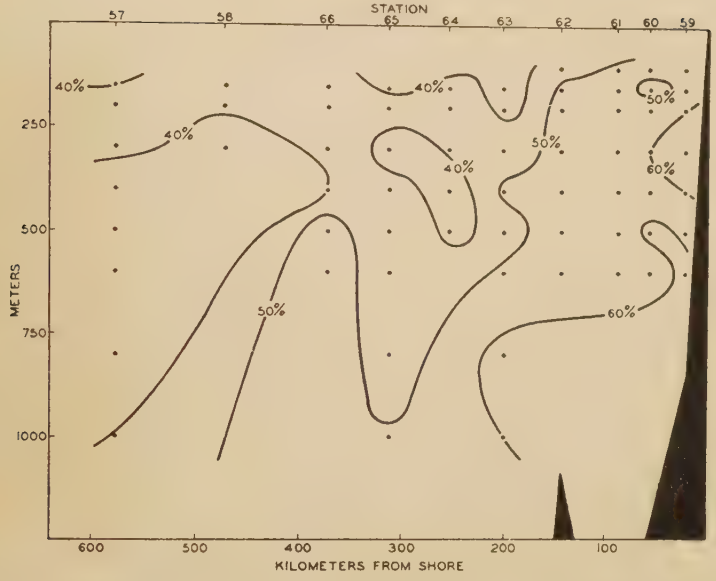

Figure 20. Section 4 off Point Dume, California, showing percentage of Equatorial water.

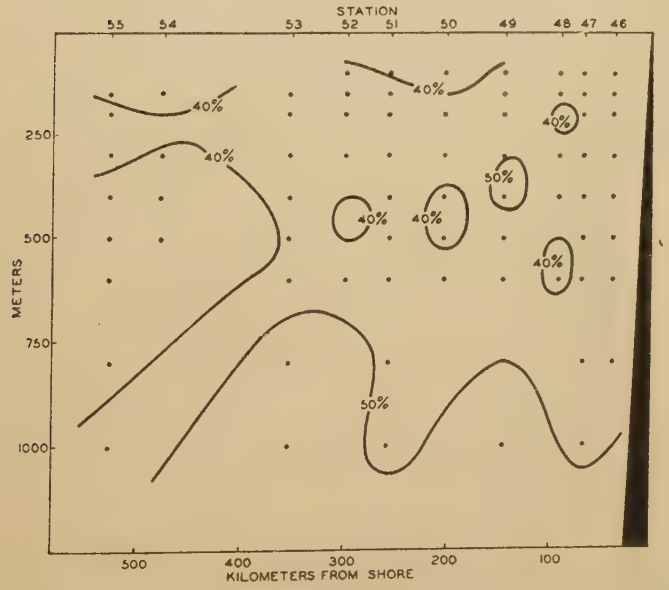

Figure 21. Section 3 off Monterey, California, showing percentage of Equatorial water.

percentages of Equatorial Pacific water obtained by entering in a diagram similar to that in Figure 17 the T-S relationships of the water at the various depths indicated in the sections, and then graphically interpolating the percentage composition at each depth. One feature of the distribution is common to all sections: the percentage is higher towards the bottom and towards the shore. This feature is especially prominent in section 6 (Figure 18) off Cedros Island, Lower California. In this region there is a remarkable intrusion of relatively warm, saline water at stations 81 and 82. In the charts of dynamic topography these correspond to the centers of two strong eddies. In section 5 (Figure 19) there is a central body of more northern water (e. g., low percentage of Equatorial water) which separates an inshore and an offshore region of higher percentage. This offshore region was, at station 77, near the center of a large eddy which appeared to bring water from the southwest into the region of observation. In section 4 (Figure 20) percentages vary from 40 near the surface and offshore to more than 60 inshore and at deeper levels. The same is true of section 3 (Figure 21) although the details of distribution are somewhat different. The two northernmost sections, 2 and 1 (Figures 22 and 23), show the lowest percentages, less than 25% of Equatorial water, but even these show some water of greater than 40%.

Figure 24 shows the percentages of Equatorial Pacific water at the 300 meter level. Again, in general, the percentages are higher inshore, the 50% curve extending as far north as Monterey, and there is a general decrease from south to north.

There is a good agreement between the distribution of the various percentages of Equatorial water and the known current pattern. The transport of warm, saline Equatorial water to the north appears to be largely accounted for by the inshore northward flow of the California Coastal Counter Current. Present data indicate that this current exists throughout the year at about 200 meters and below, and that above 200 meters it is encountered only during the winter months when it appears at the surface as a narrow, northerly coastal current (Tibby, in press). It is within the region immediately adjacent to the coast and at intermediate depths that the highest percentages are found. The general decrease in relative content of Equatorial water as the Counter Current flows north can be satisfactorily explained only on the basis of lateral mixing with the southward flowing waters of the California Current which were originally of Subarctic character and which show an increased content of Equatorial water toward the south.

It is shown here that the water at depths of from about 150 to 1000 meters off the west coast of North America is a mixture of two extreme

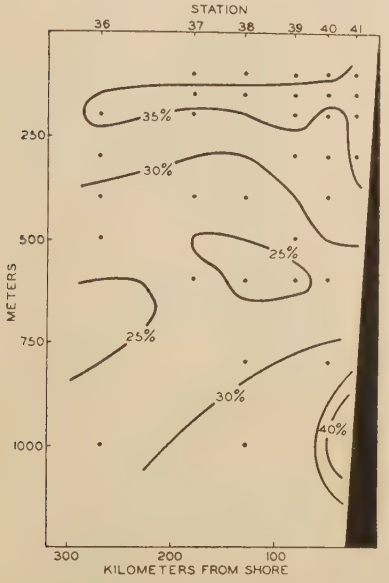

Figure 22. Section 2 off Cape Blanco, Oregon, showing percentage of Equatorial water.

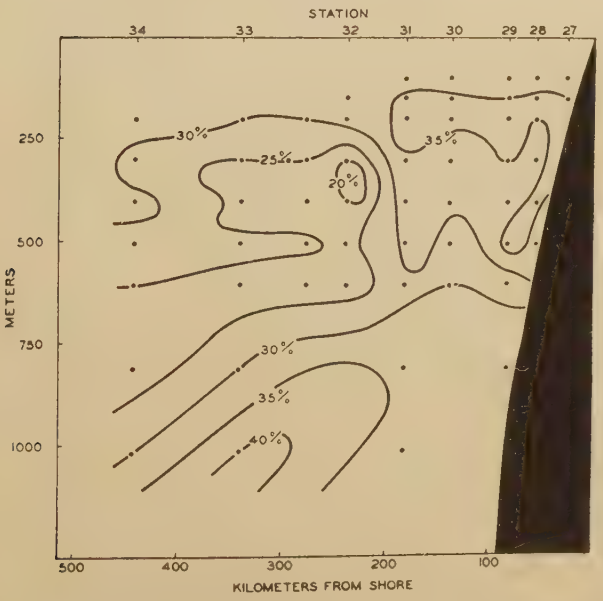

Figure 23. Section 1 off Cascade Head, Oregon, showing percentage of Equatorial water.

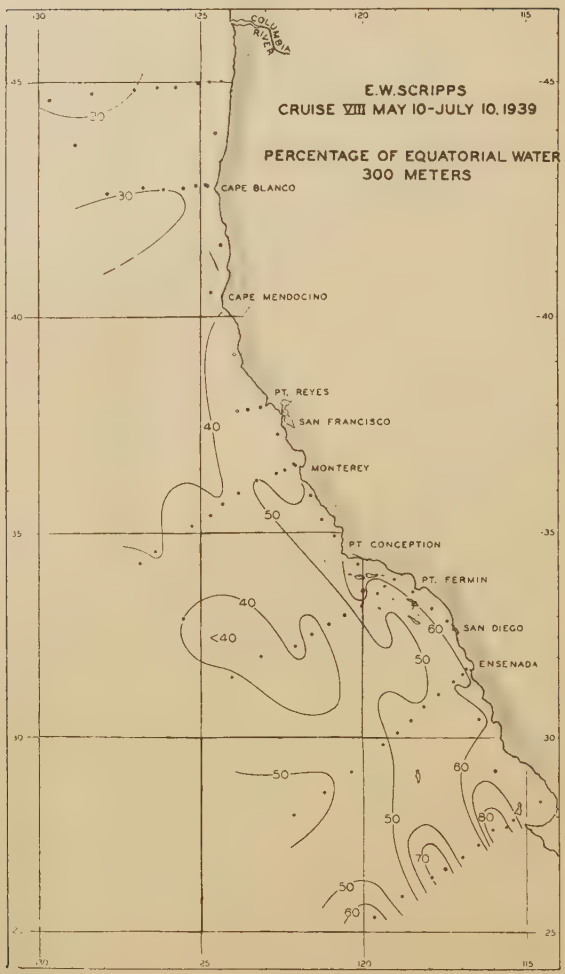

Figure 24. Chart showing percentage of Equatorial water at 300 meters.

water masses which are defined as Subarctic North Pacific and Equatorial Pacific by characteristic T-S curves. The distribution of temperature and salinity over the region of the "E. W. Scripps" Cruise VIII (from Cascade Head, Oregon, to Cedros Island, Lower California, and to some 300 miles to sea) is expressed in terms of percentages of Equatorial water. These percentages are derived by a

method based on the assumption that mixing between water masses takes place only along surfaces of equal σ_t. The distribution of these percentages is shown to be entirely consistent with the known pattern of flow in this region.

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THE ANGULAR DISTRIBUTION OF CHARACTERISTIC DIFFUSE LIGHT IN NATURAL WATERS*

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INTRODUCTION

Several investigators have conducted experiments on the angular distribution of light in natural waters (*1*, *2*). It has been found that the direction of maximum light intensity from the sun moves toward the vertical with increase in depth. It has also been found that light becomes more diffuse but remains highly directional with increase in depth. Clarke has pointed out the biological importance of the directional properties of deep water illumination (*3*). The purpose of this article is to add to the information extant on the angular distribution of light, and to present evidence that at great depths a limiting angular distribution pattern of intensity is approached. This pattern is defined as that of *characteristic diffuse light.* In another paper the author has developed a general law for the diminution of light intensity based on this concept (*4*).

FIRST MEASUREMENTS

Figure 25 shows light intensities measured in a vertical plane for 3, 6, and 9 meters. Figure 26 shows measurements in a horizontal plane for the same depths. These readings were taken in Trout Lake, Wisconsin in August 1937 with a photocell and amplifier described by the author in an article on the microstratification of inland lakes (*5*). A cylindrical hood over the apparatus confined the light received to an angular opening of about 15 degrees. The apparatus was suspended by a bifilar suspension at a given zenith angle, and then rotated in a horizontal plane. In Figure 25 the intensity from beneath is made arbitrarily equal to one for all depths. On this scale the intensity from above increases from 40 units at 3 meters to 100 units at 9 meters. The intensity from the direction of the solar beam decreases from 190

* Contribution No. 295 from the Woods Hole Oceanographic Institute.

units at 3 meters to 138 units at 9 meters. In Figure 26 the intensity in a horizontal plane in a direction opposite the sun has been made equal to one unit for all depths. Toward the sun, the intensities are about four, three, and two units respectively in order of increasing depth.

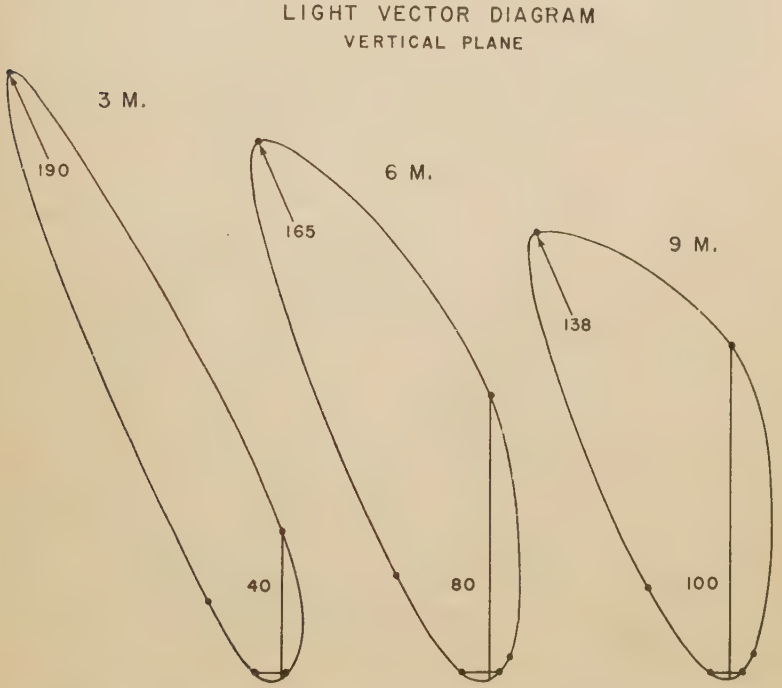

Figure 25. Light vector diagram in vertical plane including sun. Trout Lake, Wisconsin, August 1937.

The relative increase in light intensity from above as compared with the decrease from the direction of the solar beam is unmistakable. The measurements in the horizontal plane show that the light intensity becomes more symmetrical about a vertical axis as depth increases.

MEASUREMENTS WITH ROTATING PHOTOCELL

It became evident when using the original apparatus that measeurments should be taken at close intervals in the vicinity of the maximum intensity. It also seemed advisable to revise the apparatus for rapid

rotation in a vertical plane. As a matter of fact, speed in readings is of the utmost importance since the zenith angle of the sun changes continuously. This angular change is often greater than the change one is attempting to measure. High sensitivity is also of utmost importance.

The new apparatus consisted of a water tight brass cylinder which contained a photocell, amplifying tube, three small dry cells for C

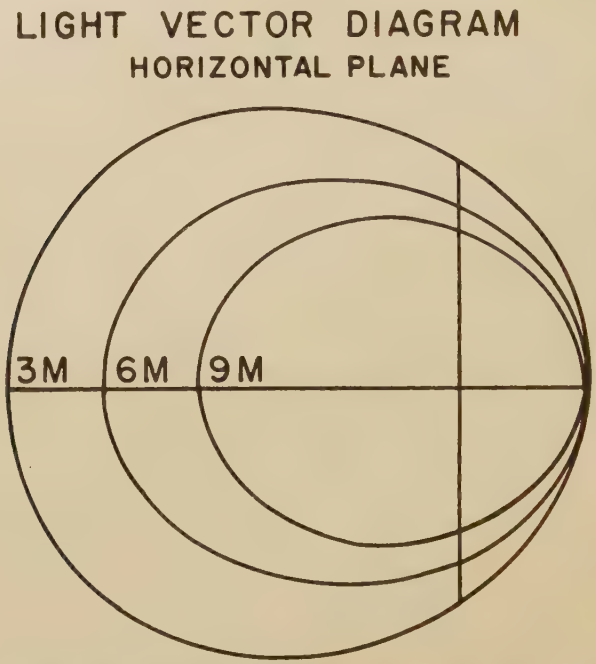

Figure 26. Light vector diagram in horizontal plane. Trout Lake, Wisconsin, August 1937.

bias, and a rotating screen which permitted different amounts of light to enter the photocell. The screen was controlled by an electromagnet. A hood with several diaphragms to eliminate reflected light confined the light received to a 15 degree angle. The cylinder was connected to the control box by means of a 100 meter four wire cable. The control box contained a second stage of amplification, necessary meters, and batteries. The circuit was similar to the one used in micro-stratification work. The cylinder was free to rotate on a horizontal axis and was supported in a frame which hung vertically from a

bifilar suspension. A ratchet mechanism attached to the cylinder caused a rotation of 10° each time a cord was pulled. After the last pull, the cylinder automatically returned to the starting position by action of a spring. The work with this apparatus was done at the Woods Hole Oceanographic Institution.

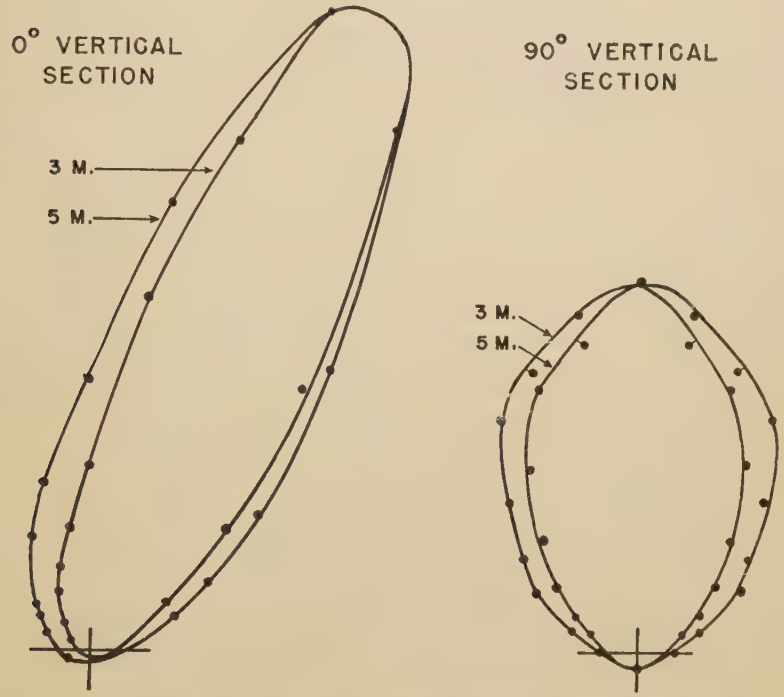

Figure 27. Vertical section light vectors. Woods Hole Harbor, August 23, 1939.

Figure 27 shows readings taken August 23, 1939 in Woods Hole Harbor at 3 and 5 meters in depth. The 0° vertical section is the vertical plane including the sun; at right angles to this plane is the 90° vertical section. For purposes of comparison the maximum readings are made to coincide. It has been stated that light becomes more diffuse in deep water; the contrast between these two sections suggests a new meaning to the idea of diffuseness in natural waters. The pattern of the 0° vertical section is broader at 5 meters than at 3 meters, while the 90° pattern is just the reverse, being narrower at 5 meters. Probably an equilibrium condition is being approached in

which light intensity tends to become symmetrical about a vertical axis.

Further evidence of this fact is to be found in certain readings of the 0° vertical section. The ratio of the 90° zenith angle reading, to the 270° zenith angle reading, or the horizontal reading toward the sun compared to the horizontal reading away from the sun, becomes closer to unity at greater depths. This ratio is 2.1 at 3 meters and 1.4 at 5 meters. The ratio of the maximum reading to the 0° zenith angle also tends to approach unity. The values of this ratio are 3.8, 2.4, and about 1.4 at depths of 3, 5, and 8 meters respectively.

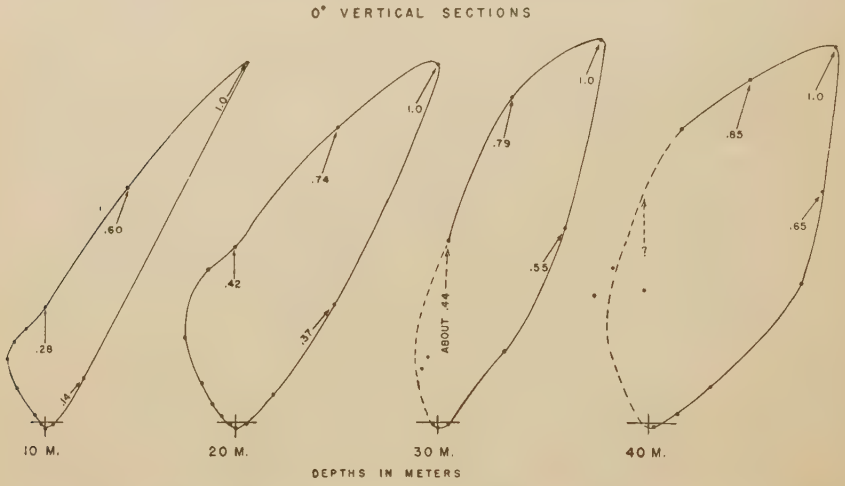

Figure 28. Vertical section light vectors. Taken just beyond Continental Shelf, September 2, 1939.

The second set of readings was taken from the research ship, Atlantis, just beyond the Continental Shelf at 39° 34′ N. latitude and 71° 05′ W. longitude. The water was more transparent and had fewer scattering particles than the Woods Hole Harbor water. The Atlantis did considerable rolling and pitching, but readings were sufficiently definite to confirm the tendencies shown by the first set of readings in Woods Hole Harbor. The apparatus was suspended from a boom over the stern of the vessel. Figure 28 shows 0° vertical sections with the maximum reading for each depth set equal to unity. The proportionate 0° zenith angle reading and the readings each side the maximum are shown numerically on the figure. The zenith reading becomes relatively greater in deeper water. The readings each side the maxi-

mum also become relatively greater; in other words, the maximum become broader. Under the experimental conditions any attempt to measure accurately the shift in zenith angle of maximum intensity was out of the question, but there was some shift toward the zenith with depth. There is no question that the pattern broadened with depth.

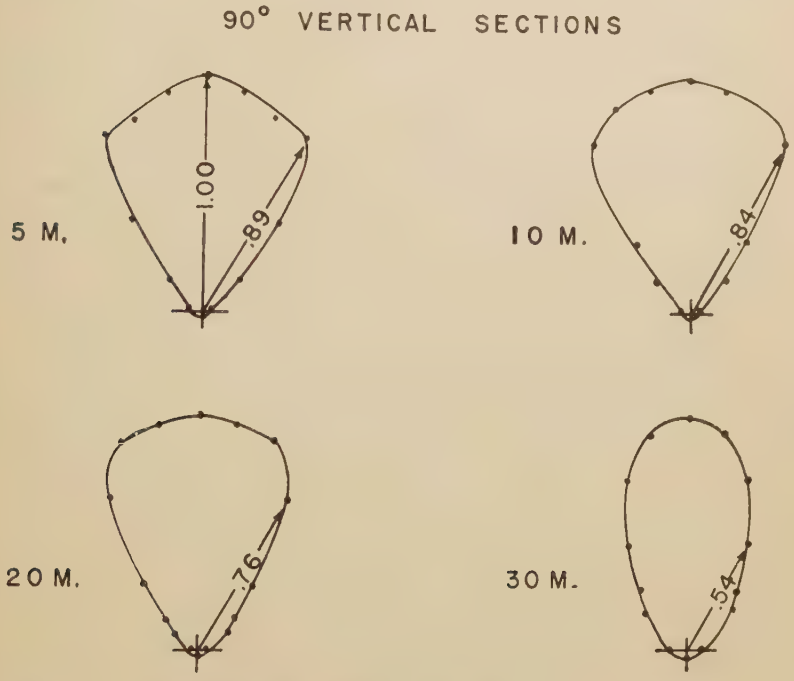

Figure 29. Vertical section light vectors. Taken just beyond Continental Shelf, September 2, 1939.

The 90° vertical sections illustrated in Figure 29 also show the reverse tendency as depth increases. For purposes of comparison, the 30° zenith angle reading is expressed in terms of the maximum. For example, a large 30° reading relative to the maximum would mean greater diffusion in the sense of equality of light from all directions. But as depth increases, or, as the diffusion approaches the maximum amount possible, the light becomes more directional from the zenith. The broader tops of the shallow water curves are probably due to the fact that the refracted rays from the sky have not as yet lost their

predominance. At 30 meters the direct rays from the sky have become relatively insignificant. An elongated oval-like pattern is approached which is evidence of the small amount of scattering in this water. Since the pattern represents approximately the maximum diffusion in deep water, it may be defined as that of characteristic diffuse light. The idea that maximum (or ultimate) diffusion means equality of

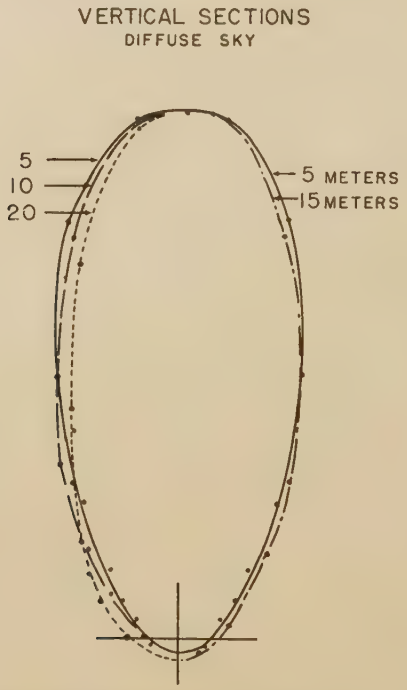

Figure 30. Vertical section light vectors under conditions of evenly clouded sky. Taken ¾ mile SSE of Tarpaulin Cove Light in Vineyard Sound, August 26, 1939.

light intensity in all directions ignores the fact that the light source itself must be in some particular direction.

The readings shown in Figure 30 were taken with a completely clouded and diffuse sky. The sun was entirely obscured and only one vertical section was taken. It was assumed that other vertical sections would be the same. The readings were obtained about ¾ miles S. S. E. of the Tarpaulin Cove Light in Vineyard Sound. It might be expected that these curves should be similar to the 90° vertical section curves of Figure 29 since a clouded diffuse sky and a clear uniform blue sky

should furnish approximately equal light intensities at all angles. However, the water beyond the continental shelf was clearer and subject to less scattering; hence the slower loss in the directional properties of the sky light as contrasted with the more rapid loss in the Sound. That this rapid loss is due to the character of the water and not to the condition of the sky is shown in the 90° vertical section of Figure 27. These readings were taken in bright sunlight but there is a rapid loss of the directional properties of the sky radiation due to the higher turbidity of the water in Woods Hole Harbor. As a matter of fact, there is little evidence of a broad top to the curve even at 3 meters.

Several interesting facts stand out upon a careful examination of Figure 30. There is a regular change in the curves as deeper water is reached; the upper portions become uniformly narrower, the lower portions broader. It seems obvious that there must be a limit to this process; it may be that the limiting pattern is symmetrical not only about a vertical axis but also about a horizontal plane as well. This possibility suggests theoretical investigation.

The fact that the changes are small seems good evidence that the pattern is practically that of characteristic diffuse light. The shape of this pattern probably depends on the relative values of the absorption and scattering coefficients. Possibly a theoretical derivation of such characteristic curves can be worked out.

It seems reasonable that the characteristic pattern will be approached rapidly, or within a short distance of the surface, if total absorption or scattering is large. The shape of the pattern approached should depend on the relative values of the absorption and scattering coefficients.

In Figure 30 and in many other sets of readings taken, it has been found that the reading vertically downward is approximately half the reading taken in a horizontal direction. This seems to be true where readings are symmetrical about a vertical axis as, for example, when readings are taken in deep water. Of course, light intensities directed upward in deep water are often too faint to be reliable. The following approximate and incomplete line of reasoning, however, suggests that there may be some significance to this two to one ratio of intensities. Assume that a light receiver has unit cross section and that it receives light in a horizontal direction from a column of unit cross section extending an infinite distance horizontally from the receiver. Assume also that the total light striking the receiver is the summation of all the amounts scattered toward the receiver, and reduced in accordance with the exponential law. This gives for the horizontal intensity:

$$I_h = \int_0^\infty fI'e^{-ky}dy = fI'/k.$$

The amount scattered *from* each contributing element of volume is proportional to I' the total light intensity at the level of the contributing elements and which is constant for this integration, to dy the thickness of each contributing layer, and to f a constant of proportionality which is a measure of the scattered light sent toward the receiver. The amount contributed from below yields a similar expression with the single exception that the light intensity at the level of the contributing elements is no longer constant but equals $I'e^{-kx}$ where I' remains the light intensity at the level of the receiver. Performing this integration the intensity upward is:

$$I_u = fI'\int_0^\infty e^{-2kx}dx = fI'/2k.$$

This is half the horizontal intensity. This treatment assumes that f, the proportionality constant for scattered light, is the same in all directions. This assumption is discussed by the author in the paper on the general diminution law (4).

DISCUSSION

Measurements of the angular distribution of light in natural waters show that as light reaches greater depths the directional properties of the refracted sun and sky light become less important. Light intensities in a vertical plane passing through the sun, or in the 0° azimuthal plane, show diminishing intensities toward the sun and a general broadening with depth. Readings taken in the 90° azimuthal plane, or readings taken in a vertical plane when the sky was uniformly clouded, showed a narrowing of the pattern with depth. In both planes the relative intensity toward the zenith increased. In all cases a pattern which is symmetrical about a vertical axis is approached in deep water.

The limiting angular distribution pattern seems to be oval shaped, possibly symmetrical about a horizontal plane as well as about a vertical axis. The exact shape of the pattern is probably a function of the scattering and absorption coefficients. Experiment and theory lead to the belief that a reading taken with the receiver face down should be half the reading in a horizontal direction.

SUMMARY

1. The angular distribution of light intensity was studied in Trout Lake, Wisconsin, Woods Hole Harbor, beyond the Continental Shelf, and in Vineyard Sound.

2. Evidence pointed to a limiting pattern in each case. The pattern is defined as that of *characteristic diffuse light.*

3. The pattern is approximately oval shaped and elongated toward the zenith.

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RADIUM CONTENT OF OCEAN BOTTOM SEDIMENTS FROM THE ARCTIC OCEAN, BERING SEA, ALASKA PENINSULA, AND THE COASTS OF SOUTHERN ALASKA AND WESTERN CANADA

By

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The radium content of several surface bottom samples in the region of the San Juan Archipelago and Vancouver Island have been reported previously (*15*). The present paper deals with the radium content of both surface bottom and core samples taken along the Pacific coast of Canada and the coast of Alaska, in the Pacific Ocean, Bering Sea and the Arctic Ocean.

The surface bottom samples were collected by means of a telegraph snapper or clam shell which sampled the bottom to a depth of several centimeters. The samples were prepared as previously reported (*15*). The experimental procedure and apparatus used for the determination of the radium content of the samples was essentially the same as that developed by Evans (*2*).

The location of the stations as well as the radium content of the samples, in grams of radium per gram of dry material, is tabulated in Table I. The results are indicated in Figure 31, in which the diameter of each circle is proportional to the radium concentration of the sample taken at the indicated station. Figure 32, which is a more detailed map of the Southern Alaska coast and Queen Charlotte Islands, shows the location of the stations and the radium content of the samples in this region. The average of 74 determinations is 0.74×10^{-12} grams of radium per gram. The radium concentration of deep sea samples as reported by various investigators (*3*, *4*, *7*, *8*, *9*, *10*) varied from 5 to 10 times this value. The low concentrations were much more pronounced in the vicinity of Vancouver Island, where the average was 0.34×10^{-12} grams of radium per gram of dry material (*15*). It will be noticed that the highest average is from the region of the southern Alaska coast where the inland passages are more or less protected by islands from the open ocean and where most of the rivers rise from the glacial slopes of the nearby granitic Rocky Mountains. The lowest averages are from the volcanic Alaska Peninsula and the Queen Charlotte Island regions which are open to the ocean and are devoid of rivers of any size.

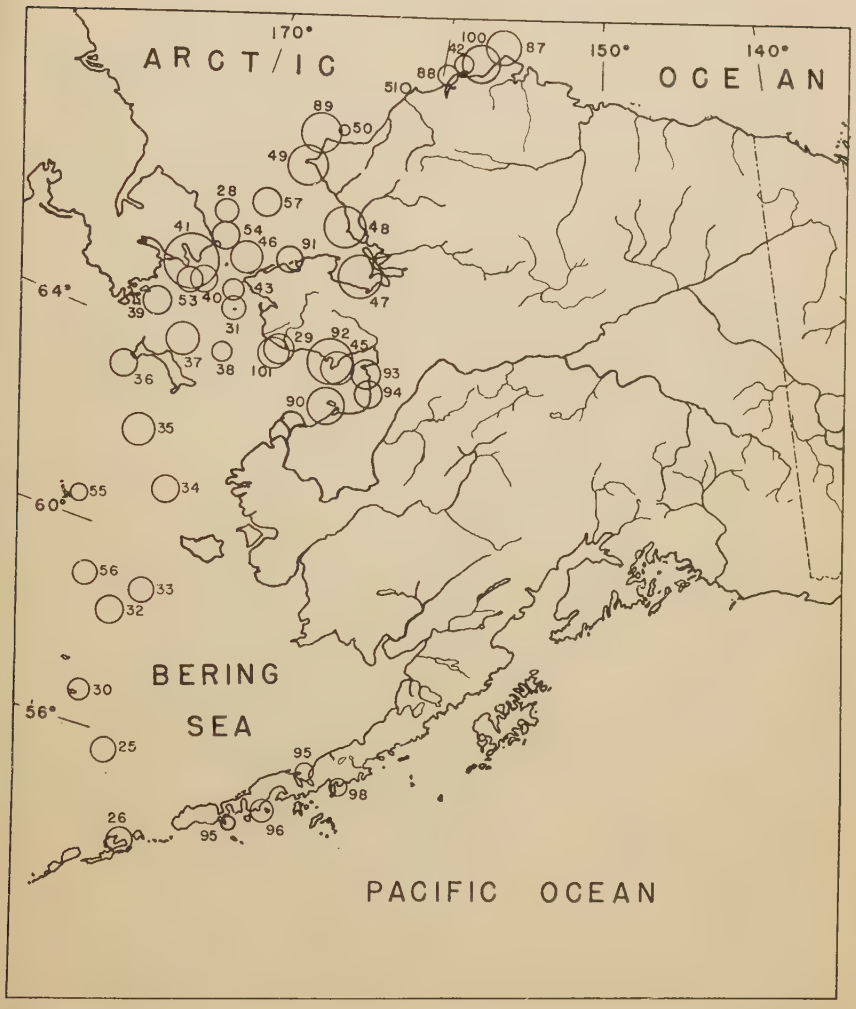

Figure 31. Chart of the Pacific coast, Bering Sea, and Arctic Ocean regions. The diameter of the circles is proportional to the radium content.

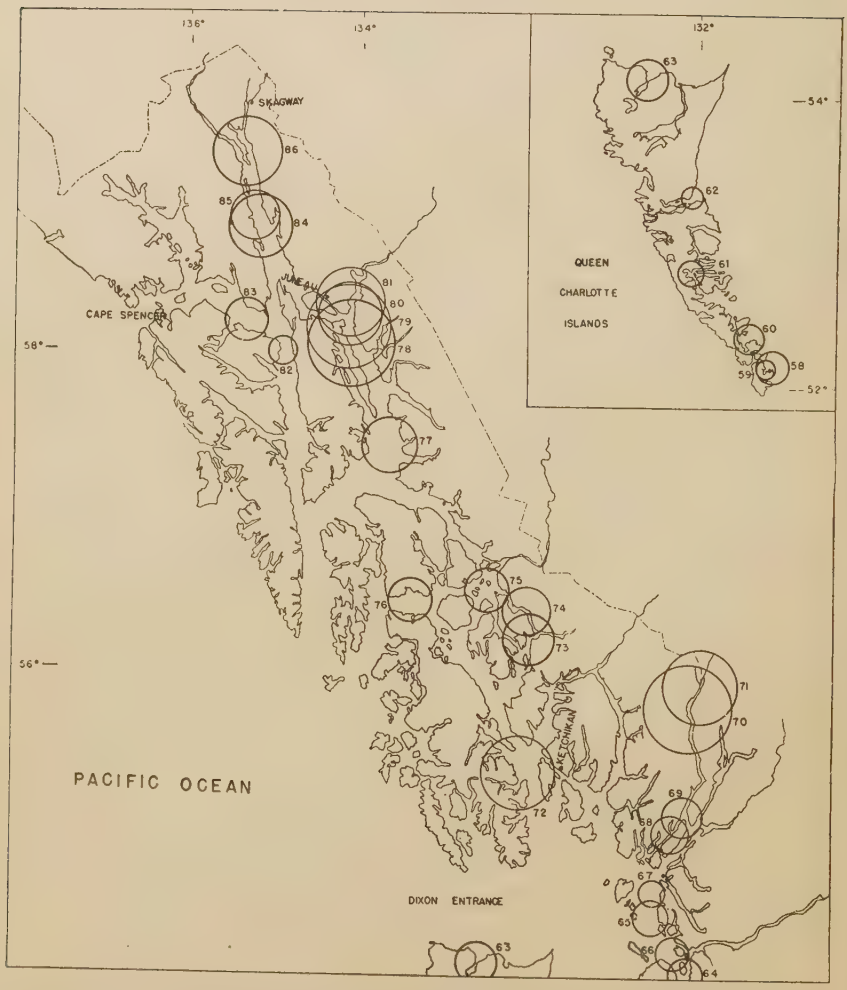

Figure 32. Chart of the southern Alaska coast and Queen Charlotte Islands regions. The diameter of the circles is proportional to the radium concentration.

TABLE I

LOCATION OF STATIONS AND RADIUM CONCENTRATION OF SAMPLES

Location	*Station*	*Latitude*	*Longitude*	*Depth (meters)*	*Radium concentration in 10^{-12} g. Ra per g.*
Arctic	28	66° 46′ N.	170° 01′ W.	47	.53 ± .01
Ocean	42	70° 55′	158° 67′	25	.42 ± .01
	46	66° 03′	168° 14′	53	.74 ± .01
	47	66° 12′	162° 40′	14	.96 ± .01
	48	67° 06′	164° 00′	21	.92 ± .01
	49	68° 19′	166° 41′	20	.90 ± .01
	50	69° 24′	165° 03′	33	.41 ± .01
	51	70° 14′	162° 47′	30	.24 ± .01
	54	66° 23′	169° 40′	49	.60 ± .01
	57	67° 21′	167° 35′	40	.64 ± .02
	87	71° 30′	156° 40′	16	.79 ± .02
	88	70° 42′	159° 58′	14	.45 ± .01
	89	68° 54′	166° 54′	43	.90 ± .03
	91	66° 12′	166° 12′	9	.58 ± .01
	100	71° 09′	158° 00′	40	.84 ± .01
				Average:	0.66×10^{-12}
Norton	29	64° 10′ N.	165° 37′ W.	22	.70 ± .01
Sound	45	64° 18′	162° 42′	15	.76 ± .01
	90	63° 39.5′	162° 23′	14	.83 ± .01
	92	64° 27′	162° 56′	9	1.01 ± .01
	93	64° 18.5′	161° 84′	10	.63 ± .01
	94	63° 52′	160° 57′	1	.84 ± .01
	101	64° 18′	165° 33′	21	.78 ± .01
				Average:	0.79×10^{-12}
Bering	25	55° 36′ N.	168° 11′ W.	131	.58 ± .01
Sea	27	65° 37′	170° 58′	33	1.21 ± .02
	30	56° 36′	169° 37′	20	.48 ± .01
	31	64° 57′	168° 06′	42	.52 ± .01
	32	58° 26′	169° 06′	64	.61 ± .01
	33	58° 46′	168° 08′	46	.57 ± .01
	34	61° 08′	168° 22′	37	.60 ± .01
	35	62° 16′	170° 32′	55	.73 ± .02
	36	63° 09′	172° 17′	51	.59 ± .02
	37	64° 03′	169° 57′	31	.75 ± .02
	38	64° 06′	168° 20′	35	.45 ± .02
	39	64° 35′	171° 21′	37	.65 ± .01
	40	65° 21′	170° 02′	44	.59 ± .01
	43	55° 18′	168° 25′	52	.51 ± .01
	44	65° 48′	168° 30′	45	.91 ± .02
	53	65° 25′	170° 31′	37	.55 ± .01

TABLE I (*Cont.*)

Location	*Station*	*Latitude*	*Longitude*	*Depth (meters)*	*Radium concentration in 10^{-12} g. Ra per g.*
Bering	55	60° 22′	172° 10′	31	.38 ± .01
Sea	56	58° 57′	171° 03′	75	.55 ± .01
				Average:	0.65×10^{-12}
Alaska	26	53° 57′ N.	166° 31′ W.	123	.59 ± .01
Peninsula	95	55° 56′	160° 40′	16	.39 ± .01
	96	55° 14′	161° 59′	100	.50 ± .01
	97	54° 48′	163° 16′	70	.33 ± .01
	98	55° 52′	159° 30′	34	.40 ± .01
				Average:	0.44×10^{-12}
Southern	64	53° 55′ N.	130° 08′ W.	36	.63 ± .01
Alaska	65	54° 16′	130° 32′	80	.65 ± .02
and	66	54° 05′	130° 15′	72	.60 ± .01
Canadian	67	54° 30′	130° 25′	48	.47 ± .02
Coasts	68	54° 58′	130° 22′	170	.68 ± .01
	69	55° 03′	130° 12′	200	.72 ± .01
	70	55° 44′	130° 09′	80	1.57 ± .02
	71	55° 51′	130° 03′	240	1.32 ± .01
	72	55° 18′	132° 09′	55	1.38 ± .02
	73	56° 11′	132° 00′	370	.93 ± .03
	74	56° 21′	131° 59′	165	.86 ± .02
	75	56° 29′	132° 29′	135	.79 ± .01
	76	56° 26′	133° 27′	22	.81 ± .01
	77	57° 22′	133° 40′	130	1.00 ± .02
	78	58° 04′	134° 05′	100	1.55 ± .02
	79	58° 07′	134° 07′	214	1.50 ± .02
	80	58° 12′	134° 07′	190	1.13 ± .02
	81	58° 17′	134° 06′	100	1.24 ± .02
	82	57° 56′	134° 50′	460	.53 ± .02
	83	58° 09′	135° 16′	146	.77 ± .01
	84	58° 43′	135° 10′	310	1.14 ± .02
	85	58° 49′	135° 13′	248	.86 ± .01
	86	59° 14′	135° 20′	91	1.25 ± .01
				Average:	0.97×10^{-12}
Queen	58	52° 05′ N.	130° 50′ W.	225	.60 ± .02
Charlotte	59	52° 06′	130° 55′	20	.41 ± .01
Islands	60	52° 14′	131° 10′	113	.55 ± .02
	61	52° 48′	131° 56′	100	.48 ± .01
	62	53° 15′	131° 56′	35	.40 ± .01
	63	54° 03′	132° 36′	13	.75 ± .01
				Average:	0.53×10^{-12}

Through the kind cooperation of Dr. G. A. Young, Chief Geologist of the Department of Mines and Resources of Canada, it was possible to obtain representative rocks from the underlying drainage basin of the Skeena River. The average radium content of these samples was 0.64×10^{-12} grams of radium per gram, while the average of the samples taken in the region of the mouth of the Skeena River was 0.63×10^{-12} grams of radium per gram. While the data seems to indicate that the radium content of inshore samples tends to approach that of the adjacent land areas, the number of samples analyzed do not permit of a general conclusion.

During the course of the experiments, it was observed that the radium content of the samples obtained from the region of glacier-fed inlets was approximately twice that of the other off-shore samples. These are tabulated in Table II. The exact reason for this greater concentration is not quite clear. It has been observed that the highest radium concentration seems to exist in the fine grained portions of a bottom sediment (*3*, *6*). This was found to be true in the case of a single sample of very fine sediment which was secured at a depth of 1730 meters approximately a hundred miles off the coast of northern Washington. This sample was accidently brought up in a water bottle and no doubt represents the very top surface of the ocean bottom. The sediment was very fine and required several days to settle out. The radium concentration was $(2.32 \pm 0.02) \times 10^{-12}$ grams of radium per gram.

Trask (*14*) has pointed out that the sediments of enclosed bodies of water that have narrow connections to the ocean are in general fine

TABLE II

RADIUM CONCENTRATION IN GLACIER-FED INLETS

Location	*Station*	*Latitude*	*Longitude*	*Depth (meters)*	*Radium concentration in 10^{-12} g. Ra per g.*
St. Lawrence Bay (Sibera)	27	65° 37′ N.	170° 58′ W.	33	$1.21 \pm .02$
Golovin Bay (Norton Sound)	92	64° 27′	162° 56′	9	$1.01 \pm .01$
Lynn Canal	86	59° 14′	135° 20′	91	$1.25 \pm .01$
Taku Inlet	81	58° 17′	134° 06′	100	$1.24 \pm .02$
Taku Inlet	80	58° 12′	134° 07′	190	$1.13 \pm .02$
Taku Inlet	79	58° 07′	134° 07′	214	$1.50 \pm .02$
Taku Inlet	78	58° 04′	134° 05′	100	$1.55 \pm .02$
Portland Canal	71	55° 51′	130° 03′	240	$1.32 \pm .01$
Portland Canal	70	55° 44′	130° 09′	80	$1.57 \pm .02$
				Average:	1.31×10^{-12}

grained and comparable to deep ocean deposits. While the mechanical analysis of the sediments is incomplete. sufficient data is available for some comparison of sample No. 81 which has a radium content of 1.24 x 10^{-12} grams of radium per gram with sample No. 42 which contains 0.42 x 10^{-12} grams of radium per gram. Sample No. 81 was taken at the foot of Taku Glacier. It is composed in part of particles of glass or ash, which have a maximum diameter of 0.2 mm. and an average diameter of 0.05 mm. These particles comprise about one-half the bulk of this sample. The other constituents of this sample vary in diameter from 0.01 mm. to 0.001 mm. Approximately 80% of these small particles are volcanic glass and the remainder are clear minerals such as quartz, mica, zircon, and augite. Sample No. 42, which was taken in shallow water near the coast of Alaska in the Arctic Ocean, contained several large particles of water-washed sand which varied from 0.35 mm. to 0.40 mm. in diameter. Most of the particles in this sample averaged about 0.2 mm. in diameter. The smallest particles

TABLE III

Variation of Radium Concentration along Core Samples

Location	*Sample Number*	*Latitude*	*Longitude*	*Depth (meters)*	*Depth from Surface*	*Radium concentration in 10^{-12} g. Ra per g.*
St. Lawrence	152	65° 35′ N.	107° 51′ W.	27	1 cm.	1.15 ± .01
Bay	155				7	1.04 ± .02
	154				15	0.95 ± .02
Bering Sea	173	67° 21′	167° 35′	40	1	0.59 ± .01
	165				8	0.57 ± .01
	168				16	0.59 ± .01
Norton Sound	174	64° 20′	166° 15′	24	1	0.66 ± .01
	167				14	0.71 ± .01
East Sound	151	48° 36′	122° 52′	42	1	0.43 ± .02
Olga	142				14	0.47 ± .01
Rosario	146	48° 40′	122° 54′	28	1	0.52 ± .02
	141				14	0.51 ± .01
Tacoma	185	47° 16′	122° 33′	− 1.5	3 m.	0.44 ± .02
(Washington)	186				6	0.61 ± .01
Narrows	187				12	0.54 ± .02
Bridge	188				15	0.52 ± .02
	189				21	0.52 ± .01
	190				28	0.48 ± .01
	191				31	0.63 ± .02
	192				37	0.58 ± .03

averaged 0.01 mm. diameter and consisted mostly of a glassy ash. The sample contained garnet, mica, feldspar and zircon.

Several short cores, approximately 15 cm. in length, were secured from the Arctic Ocean and the Bering Sea by driving a pipe into the ocean bottom by means of a weight attached to the cable. The location of the stations and radium content of the cores is given in Table III. That no consistent variation of radium concentration with depth was observed is in agreement with the results reported by other investigators (*9*, *12*). Since these short cores were collected, a Piggot Core Sampler (*11*) has been provided and put into use. Analyses of several cores, varying from 7 to 10 feet in length, are now in progress, the results of which will be tabulated and presented when they are completed.

Two cores, 14 cm. in length, were obtained in East Sound in the San Juan Archipelago. This sound is very rich in plankton during the spring and summer months. While plankton has been reported (*2*, *5*) as containing from 100 to 1000 times as much radium per gram as the sea water in which they live, their role as a carrier of radium to the ocean bottom has been shown to be insignificant (*5*, *13*). This is substantiated by the analyses of the cores taken from East Sound, since the radium concentration is not greater than those from the surrounding area (*15*) and shows no variation with depth.

Through the kindness of Mr. L. V. Murrow of the Washington Toll Bridge Authority samples, to a depth of 120 feet, were obtained from the survey made for the purpose of locating the piers of the Tacoma Narrows Bridge. This region was once covered by Pacific Ocean waters. This core, which was the only one of appreciable length, does not fall in either of the two classes of deep sea cores as designated by Piggot and Urry (*13*).

TABLE IV

Radium and Selenium Concentration

Station	*Latitude*	*Longitude*	*Depth (meters)*	*Radium concentration in 10^{-12} g. Ra per g.*	*Selenium concentration in parts per million**
25	55° 36′ N.	168° 11′ W.	131	0.58 ± .01	0.30
26	53° 57′	166° 31′	123	0.59 ± .01	0.30
27	65° 37′	170° 58′	33	1.21 ± .02	0.40
28	66° 46′	170° 01′	47.5	0.53 ± .01	0.25
29	64° 10′	165° 37′	22	0.70 ± .01	0.20
30	56° 36′	169° 37′	20	0.48 ± .01	0.03
101	64° 18′	165° 33′	21	0.78 ± .01	0.25

* Determined by Williams and Byers.

Selenium determinations have been made by Williams and Byers (*16*) on seven of the samples from which radium determinations were made. The radium and selenium content of these seven samples are given in Table IV. It will be noted that there is no apparent correlation between the radium and selenium content. Both radium and selenium are found in soil and river waters as well as ocean sediment. However, no selenium was found by Byers and others (*1*) in ocean water while the radium concentration in ocean water is found to be of the order of 1.0×10^{-16} grams of radium per cc. of water (*3*, *5*).

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THE SODIUM-CHLORINITY RATIO OF OCEAN WATERS FROM THE NORTHEAST PACIFIC

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Ocean water is a complex solution of many ions. The concentration of this solution varies considerably from place to place but it has been repeatedly shown that the relative concentration of the ions to each other is remarkably constant. The composition of an average water sample having a chlorinity of 19.374 °/₀₀ is given by Thompson (*5*) as follows:

TABLE I

Composition of an Ocean Water, Cl = 19.374 °/₀₀

Cations	*Grams per Kilogram*	*Equivalents per Liter*
Na^+	10.722	0.4662
Mg^{++}	1.297	0.1067
Ca^{++}	0.417	0.0209
K^+	0.382	0.0098
	12.818	0.6036

Anions	*Grams per Kilogram*	*Equivalents per Liter*
Cl'	19.337	0.5453
SO_4''	2.705	0.0564
HCO_3'	0.097	0.0016
CO_3''	0.007	0.0002
Br'	0.066	0.0008
	22.212	0.6043

Sodium is by far the outstanding major cation and it would be supposed that its relative concentration, expressed as the sodium-chlorinity ratio, would be quite accurately known. There has been, however, considerable difference of opinion in regard to this ratio as the following summary (*6*) shows:

TABLE II

SUMMARY OF PREVIOUS WORK

Investigator	*Location*	*Number of Samples*	*Na/Cl Ratio (by Weight)*
Dittmar	All, except Polar	77	0.5514
Makin	Atlantic	22	0.5476
Schloesing	Atlantic and Mediterranean	3	0.5528
Thorpe and Morton	Irish	1	0.5573
Schmidt	Baltic and White	6	0.5536
Steiger	Atlantic	1	0.5567
Wheeler	Atlantic	5	0.5567
Schmelck	Atlantic	51	0.5504
Forsberg	Siberian	4	0.5484
Natterer	Mediterranean	42	0.5310
Kolotoff	Black Sea	1	0.5518
Anderson and Thompson	Puget Sound	12	0.5495
		225	
		Weighted Average	0.5509
		Mean	0.5523

The reasons for these variations may be partly due to the manner of storing the samples and the methods of analyses. In general, sodium in sea water has been determined by indirect methods. The total sulfate method, as first used by Dittmar (*2*) and followed by many others listed in Table II, consisted of taking a known weight of sea water and evaporating it to dryness with dilute H_2SO_4 to obtain the weight of the normal sulfates. Separate determinations of Ca, Mg, and K upon the same sample made it possible to calculate the weight of the Na_2SO_4 found. The chief criticism lies in the dependence of the Na determination upon the accuracy of the other determinations.

More recently Webb (*7*) proposed the Na/Cl ratio of 0.5549($\pm$0.001) as the result of analyses performed on a sample of Firth of Clyde sea water having a Cl of 18.43 °/$_{oo}$. He used a modification of the zinc uranyl acetate method as given by Robertson and Webb (*4*). As further evidence in support of this ratio, Webb computed a Na/Cl ratio of 0.5554 ($\pm$0.001) by using the SO_4/Cl, Ca/Cl, Mg/Cl, and K/Cl ratios and the excess base data generally accepted. Also, from the relationship between chlorinity and salinity, he computed a Na/Cl ratio of 0.5580 which, although probably too high due to difficulty in making accurate determinations of salinity, he believes provides confirmatory evidence supporting the higher of the several ratios hitherto suggested by the work of previous authors.

Lyman and Fleming (*3*) critically examined the results of determinations of the major ions of sea water and suggested "best values" for the various ratios with chlorinity. Knowing the values of the other main constituents they calculated sodium by difference. This value resulted in a Na/Cl ratio of 0.5556.

PREPARATION OF REAGENTS AND STANDARD SOLUTIONS

For the present study, the method of analysis was the zinc uranyl acetate procedure first introduced by Barber and Kolthoff (*1*), and applied to ocean waters by Robertson and Webb (*4*).

Zinc Uranyl Acetate:

(A) Dissolve 80 grams of $UO_2(C_2H_3O_2)_2 \cdot 2H_2O$ with heating in 425 ml. of water to which has been added 14 ml. of glacial $HC_2H_3O_2$.

(B) Dissolve 220 grams of $Zn(C_2H_3O_2)_2 \cdot 2H_2O$ with heating in 275 ml. of water to which has been added 7 ml. of glacial $HC_2H_3O_2$.

Mix solutions (A) and (B) while hot and set aside for 24 hours. Filter the solution into a Pyrex bottle and add a small amount of $NaC_2H_3O_2$ to saturate the reagent with $NaZn(UO_2)_3(C_2H_3O_2)_9$. Set the reagent aside for at least 24 hours and filter each quantity just before using.

Ethyl Alcohol:

Saturate 95% C_2H_5OH with $NaZn(UO_2)_3(C_2H_3O_2)_9$ and filter just before using.

NaCl Solutions:

The NaCl was precipitated from a saturated solution of the C. P. salt with HCl gas. It was further purified by recrystallization from water, and after drying was ignited in a platinum dish at a temperature of 500 to 600° C.

Sufficient pure, dry NaCl was dissolved in water to make a solution containing 10.70 mg. of Na per ml.

Synthetic Sea Water Solutions:

Pure $MgSO_4$, $MgCl_2$, $CaCl_2$, and KCl were dissolved in water and diluted to 500 ml. Analysis of a 25 ml. portion of this solution indicated either a negligible or a very small amount of sodium present. Pure NaCl was added to the remainder of the solution and it was diluted to 1 liter. Sufficient amounts of the salts were taken so that the concentration of the ions in the final solution was equivalent to that in a water of Cl = 19.374 °/₀₀.

PROCEDURES

Determination of Sodium:

Thoroughly wash a sintered glass crucible of porosity 20 to 30 μ with distilled water, followed by a few ml. of acetone, and finally by anhydrous ether. Remove all trace of ether from the crucible by passing air through it for about two minutes. Place the uncovered crucible in the balance case and weigh after 15 minutes.

Weigh 1 ml. of a filtered water sample in a covered 25 ml. beaker. To the weighed sample add the previously filtered zinc uranyl acetate reagent. Stir thoroughly for two minutes and then set the beaker aside for one and one-half hours. The exact volume of reagent to be used should be 10 or more times greater than the volume of the sample. In the present work, 13 ml. were used per sample.

Filter the precipitate into the crucible. Because of the high solubility coefficients of $NaZn(UO_2)_3(C_2H_3O_2)_9$, the temperature of filtering the reagents and the precipitate should be approximately the same. Use 10 ml. of the filtered C_2H_5OH reagent to wash and transfer the precipitate to the crucible. Dry the precipitate with 10 ml. of anhydrous ether added in several portions. Remove all trace of ether and weigh as before.

The composition of the precipitate is $NaZn(UO_2)_3(C_2H_3O_2)_9 \cdot 6H_2O$. Multiply the weight of the precipitate by the factor 0.01495 to obtain the weight of the Na in the sample. Convert this value to Na °/₀₀. The weighings were not corrected to in vacuo since this involved a correction of only 6 parts per 10,000 which would have an insignificant effect.

Determination of Chlorinity:

The well known Mohr volumetric procedure as adapted to sea water was used in the determination of the chlorinity. The chlorinity of check determinations was required to agree within 0.012 °/₀₀. The silver nitrate solution was standardized with Normal Water prepared by the Hydrographic Laboratories of Copenhagen.

COLLECTION AND ANALYSES OF SAMPLES

A total of 99 samples were collected for analyses by the M. S. CATALYST of the Oceanographic Laboratories of the University of Washington. Vertical series of samples were taken from three Pacific Ocean stations off the coast of Washington, two stations in the Strait of Juan de Fuca, and five stations from various portions of Puget Sound.

The samples were stored in paraffin-lined bottles and were analyzed usually within a few days of the time of collection. With each group of six sea water samples analyzed, one sample of a standard synthetic sea water solution was included. Thus the method was under careful control at all times.

RESULTS OF ANALYSES

Known Solutions:

Thirty-seven analyses of synthetic sea water solutions were made. The mean error of these determinations was -0.1%, and the average deviation from this mean was $\pm 0.2\%$. In Table III a representative sampling of these results is given. In Table III also are given the results of 5 analyses of NaCl solutions. The mean error of these determinations is essentially the same as that found for the synthetic sea water. Using this same method with NaCl solutions, Barber and Kolthoff (*1*) found errors ranging from -0.2% to $+0.7\%$. They concluded that the method gave results accurate to about 0.5%. Robertson and Webb (*4*) in analyzing NaCl solutions and synthetic sea water by this method reported errors ranging from -0.5% to $+0.4\%$, with a probable error of 0.2%.

The results of the analyses of the 45 samples from the three Pacific Ocean stations are given in Table IV. The Na content was found to range from 9.73 to 10.67 grams per kilogram of water. The mean Na/Cl ratio was calculated to be 0.5549. In Table V are given the results of the analyses of the 53 samples from the seven stations located in the Strait of Juan de Fuca and in Puget Sound. The sodium content ranged from 8.98 to 10.42 grams per kilogram of water, with the exception of one sample (Brown Point, surface, for which the Na $^{o}/_{oo}$ was 7.24). The mean Na/Cl ratio for these samples was found to be 0.5562.

For the 98 samples analyzed in all, the mean Na/Cl ratio was 0.5556. These main ratios are thought to have an accuracy of about 0.0005 with a mean deviation of 0.001.

EVALUATION OF RESULTS

The method yielded satisfactory results with synthetic sea water for the range of concentrations comparable to the Na concentration of the samples analyzed. However, observation of the results shows slightly high results for the more dilute samples of synthetic sea water and slightly low results for the more concentrated solutions. In general, this trend is summarized as follows:

Na ‰	Cl ‰	% Error
9.0– 9.4	16.0–16.7	+0.2
9.4– 9.7	16.7–17.2	+0.1
9.7–10.4	17.2–18.4	0.0
10.4–10.7	18.4–19.0	−0.1

A trend is quite evident but the errors are somewhat variable and relatively small. Consequently no corrections have been incorporated in the listed results for Na in sea water.

The calculated Na/Cl ratios for the more dilute waters of Puget Sound are slightly larger than for the Pacific Ocean. However, if these values are corrected in accordance with the errors just discussed the mean Na/Cl ratios for the Pacific Ocean samples become 0.5553 and for the Strait of Juan de Fuca and Puget Sound become 0.5555. It should be pointed out, though, that the actual results differ from these corrected results within the limits of experimental error for the method.

The value of the Na/Cl ratio for the Pacific Ocean samples, 0.5549 is identical with Webb's (*7*) value for the Firth of Clyde sample. The mean Na/Cl ratio of 0.5556 for all samples in this study is identical with the "best value" suggested by Lyman and Fleming (*3*), and is almost identical with the Na/Cl ratio of 0.5554 computed by Webb from the accepted data of the major ions present in sea water. When compared with analyses made by the total sulfate method, the Na/Cl ratio found in this study is higher than the mean ratio of 0.5523 given in Table II. However, some of the higher values given in that table do not differ greatly from 0.5556. The direct determination of sodium is thought to be more accurate than calculation by indirect methods.

SUMMARY

The sodium content of synthetic sea water and NaCl solutions was determined by means of the zinc uranyl acetate method. The mean error found for these known solutions was −0.1% with an average deviation from this mean of ± 0.2%.

The sodium content of sea water samples was determined and the following values for the Na/Cl ratio were calculated:

(A) for 46 samples from three Pacific Ocean stations off the coast of Washington,—0.5549.

(B) for 53 samples from seven stations located in the Strait of Juan de Fuca and Puget Sound,—0.5562.

(C) for the total 99 samples from the ten stations from the Pacific Ocean, Strait of Juan de Fuca, and Puget Sound,—0.5556.

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TABLE III

Determination of Sodium in Solutions of Known Concentration

NaCl Solutions

Mg. Na Taken	*Mg. Na Found*	*% Error*
10.51	10.49	−0.2
10.41	10.39	−0.2
10.33	10.30	−0.3
10.16	10.14	−0.2
9.89	9.86	−0.3

Synthetic Sea Water

Mg. Na Taken	*Mg. Na Found*	*% Error*
10.72	10.70	−0.2
10.68	10.67	−0.1
10.65	10.62	−0.3
10.29	10.29	0.0
9.99	9.97	−0.2
9.72	9.73	+0.1
9.56	9.57	+0.1
9.31	9.34	+0.3
7.81	7.86	+0.6

TABLE IV

THE SODIUM-CHLORINITY RATIO IN PACIFIC OCEAN WATERS OFF THE COAST OF WASHINGTON

Lat. 47° 40′ N. Long. 126° 20′ W.

July 24, 1940

Depth meters	*Na* ‰	*Cl* ‰	*Na/Cl*
S	9.73	17.50	0.556
10	9.76	17.60	0.555
20	9.76	17.60	0.555
30	9.80	17.66	0.555
50	9.94	17.91	0.555
75	10.00	17.99	0.556
100	10.19	18.34	0.556
200	10.41	18.76	0.555
300	10.42	18.78	0.555
400	10.43	18.82	0.554
500	10.45	18.89	0.553
800	10.52	18.98	0.554
1000	10.59	19.04	0.556
1200	10.60	19.10	0.555
1500	10.60	19.12	0.555

Lat. 47° 09′ N. Long. 126° 20′ W.

July 25, 1940

Depth meters	*Na* ‰	*Cl* ‰	*Na/Cl*
S	9.82	17.71	0.555
10	9.84	17.73	0.555
20	9.83	17.73	0.554
30	9.91	17.85	0.555
50	9.98	17.96	0.555
75	9.96	17.97	0.554
100	9.97	18.01	0.554
200	10.39	18.78	0.553
300	10.39	18.78	0.553
400	10.44	18.84	0.554
500	10.45	18.89	0.553
800	10.51	18.99	0.554
1000	10.55	19.05	0.554
1500	10.60	19.11	0.555
2000	10.64	19.17	0.555

TABLE IV (*Cont.*)

Lat. 47° 09′ N. Long. 126° 49′ W.

July 25, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	9.88	17.79	0.555
10	9.88	17.79	0.555
20	9.92	17.89	0.555
30	—	—	—
50	9.98	17.98	0.555
75	9.98	17.98	0.555
100	10.01	18.03	0.555
200	10.39	18.75	0.554
300	10.46	18.82	0.556
400	10.44	18.84	0.554
500	10.51	18.90	0.556
800	10.55	19.00	0.555
1000	10.60	19.05	0.556
1200	10.60	19.07	0.556
1500	10.62	19.12	0.555
2000	10.67	19.17	0.556

TABLE V

The Sodium-Chlorinity Ratio in Waters of the Strait of Juan de Fuca and Puget Sound

Neah Bay, Strait of Juan de Fuca

Lat. 48° 25′ N. Long. 124° 27′ W.

July 6, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	9.29	16.69	0.557
10	9.62	17.28	0.557
20	9.96	17.90	0.556
30	10.28	18.46	0.557
50	10.31	18.57	0.555
100	10.37	18.67	0.555
150	10.42	18.78	0.555
250	10.42	18.80	0.554

TABLE V (*Cont.*)

Pillar Point, Strait of Juan de Fuca

Lat. 48° 18′ N. Long. 124° 03′ W.

November 2, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	9.66	17.37	0.556
10	9.67	17.39	0.556
20	9.69	17.43	0.556
30	9.75	17.56	0.555
50	9.79	17.63	0.555
75	9.90	17.82	0.555
100	9.92	17.86	0.555
150	10.27	18.49	0.555
175	10.26	18.53	0.554

Point No Point, Puget Sound

Lat. 47° 54′ N. Long. 122° 29′ W.

November 1, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	9.43	16.93	0.557
10	9.43	16.93	0.557
20	9.41	16.94	0.556
30	9.42	16.94	0.556
50	9.44	16.96	0.557
75	9.43	16.96	0.556
100	9.44	16.96	0.556
184	9.43	16.98	0.555

Jefferson Head, Puget Sound

Lat. 47° 45′ N. Long. 122° 28′ W.

November 1, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	9.20	16.53	0.557
10	9.36	16.84	0.556
20	9.39	16.87	0.556
30	9.39	16.91	0.555
50	9.40	16.91	0.556
75	9.42	16.94	0.556
100	9.42	16.95	0.556
200	9.46	17.01	0.556
247	9.46	17.00	0.556

TABLE V (*Cont.*)

Brown Point, Puget Sound

Lat. 47° 19′ N. Long. 122° 28′ W.

July 10, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	7.24	12.99	0.557
10	9.04	16.23	0.557
20	9.05	16.26	0.557
30	9.07	16.27	0.557
50	9.06	16.28	0.556
100	9.17	16.48	0.556
170	9.22	16.58	0.556

Fosdick Point, Puget Sound

Lat. 47° 15′ N. Long. 122° 35′ W.

July 10, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	9.00	16.15	0.557
10	9.01	16.17	0.557
20	9.02	16.19	0.557
30	9.02	16.17	0.557
50	9.03	16.22	0.557
74	9.04	16.27	0.556

Devils Head, Puget Sound

Lat. 47° 10′ N. Long. 122° 46′ W.

July 9, 1940

Depth meters	*Na* °/₀₀	*Cl* °/₀₀	*Na/Cl*
S	8.99	16.12	0.558
10	8.98	16.11	0.557
20	8.99	16.14	0.557
30	8.99	16.14	0.557
50	9.01	16.15	0.558
93	9.01	16.19	0.557

SURFACE COOLING AND STREAMING IN SHALLOW FRESH AND SALT WATERS*

By

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Experimental work with thermally unstable air and liquids (Mal, 1931; Graham, 1933; Chandra, 1937; and others) has shown that the convection "cells" formed vary with the amount of shear, which is introduced either by the flow of the fluid or by the movement of its boundaries. Changes in the flight tactics of free soaring gulls over the open ocean show that the pattern of the convectional up-flow within air moving over warmer water varies with the wind speed (Woodcock, 1940). Since the air over warmer sea water moves in a fashion in part comparable to the experimental findings, it was thought that some similar motion might be observed in the water itself.

While looking for possibly related convectional changes in surface waters under natural conditions, it has been found that the first few millimeters of water on the surface of shallow bays and ponds (salt and fresh) on Cape Cod are almost continuously colder than the subsurface water under average fall weather conditions. Associated with this cooled surface film, when winds are blowing, there is invariably found a small scale streaming (Fig. 33) in which the whole surface of the water is divided into a rapidly changing pattern of currents running in lines roughly parallel to the wind direction. These streams are usually about a centimeter across, with a constantly varying distance (usually just a few centimeters) between parallel lines of flow. The surface water between the lines moves transversely to converge in the lines, where it presumably sinks. Individual lines grow or die away within a few seconds time; sometimes converging upon other lines, sometimes diverging and disappearing. The water in the streams themselves moves down-wind much faster than the water between them, which suggests that they are an accumulation of water from the surface film which has been exposed to a maximum of wind drag. This small scale linear streaming is seen on the surface of large waves in the open sea, as well as in comparatively sheltered bays and ponds (where attending thermal instability has been measured) and, in the

* Contribution No. 294, from the Woods Hole Oceanographic Institution.

shallow water, it seems to supply a mechanism whereby cooled surface layers of water are drained off to lower depths.

One of the most outstanding features of this surface streaming is the rapidity of the transverse movement of the water as indicated by the lycopodium powder broadcast on the surface. When the powder is dusted over the water it moves into lines so quickly that, even in a moderate breeze, the eye can hardly detect the transition from random scattering to the linear pattern. The speed of this motion suggests that the first few millimeters of water are being drained off to lower depths very rapidly.

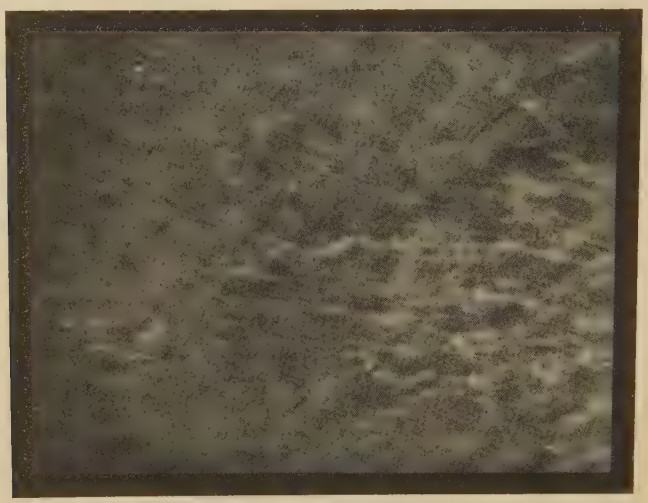

Figure 33. Surface streaming in a brackish pond, indicated by lycopodium powder.

Although the thermally unstable film on relatively open waters and the attending small scale streaming are not commonly recognized, experimental work in fluids by Rayleigh (1916), Phillips and Walker (1932), Mal (1931), and others has shown that thermal instability (introduced by heating below or cooling above), accompanied by sufficient shear, produces longitudinal strip-like convection cells extending in lines parallel to the direction of flow. In liquids they found that the motion was down in the lines and up between them.

Under natural conditions the cooled surface layer of sea water and lake water, plus the shear introduced by winds, apparently produces a patterned surface streaming comparable to the strip-like convection motions produced experimentally. Observations under natural con-

ditions have not been made when there was no possibility of heat loss from the surface film, so there is no positive assurance that the streaming cannot occur in stable water under a wind-produced shear. However, Brunt (1937, p. 283) remarks that ". . . shear does not of itself facilitate the formation of vertical circulations" in unstable air. Whether or not shear facilitates the formation of vertical circulations in stable salt and fresh surface waters remains unknown.

Langmuir (1938) made measurements of large scale surface streaming (5 to 25 meters between "streaks") in relatively deep water on a lake, and referred to it as "wind induced." He found sinking water

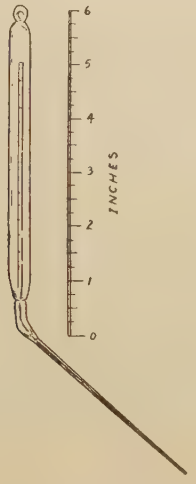

Figure 34. Thermometer used for making surface temperature measurements.

under the streaks and ascending water between them, and the slower moving surface water converged upon the lines transversely. He did not associate this motion with thermal instability, though he did say that during late fall "the descent of masses of denser water cooled by exposure on the surface" might accelerate it (p. 123).

The similarity of the surface motion in the small streams to the surface motion in Langmuir's streaks suggests that they may have a common origin, especially when we consider that the smaller is often found superimposed upon the other. In both cases, when winds are blowing, the surface water between the lines moves to the right and left of the wind to converge in the lines, and the down-wind motion of the water in the lines is faster than the down-wind motion of

the water between the lines. The experimental work in thermally unstable films indicates a need for both shear and instability for the formation of the strip-like lines of convergence. However, Langmuir's work on open water suggests that wind shear alone is enough. Perhaps the common occurrence of a rapidly produced unstable surface film on lakes and bays may serve to indicate a possible answer to the question raised, for it seems that this layer might supply the potential energy to drive the vertical circulations in Langmuir's "helical vortices" as well as in the experimental "cells."

Adney (1926) has demonstrated experimentally that the rate of solution of oxygen and nitrogen in de-aerated fresh and salt water is increased a great deal by vertical "streaming" due to surface cooling by evaporation. He found the resulting mixing more effective in salt water, which he said is due "largely if not wholly to the fact that in addition to the cooling effect of evaporation at the surface film, there is also that of concentration of the salts in solution" (p. 214). It seems reasonable to suppose that the surface cooling and streaming which is discussed here serves a similar purpose, under natural conditions, of carrying down oxygen and nitrogen saturated surface waters.

Variations in the spacings of the streams may prove useful as an indication of the depth to which the streams penetrate. In experimental treatment of the "strip" convection cells in unstable fluids, the horizontal dimensions are found to be twice the depth (or height) of the instability layer (Durst, 1932, p. 58). Casual observations of the distances between lines in surface waters on the open sea show that they vary from a few centimeters across up to 100 meters or more. Strip-like lines in air (indicated by mist rising from warm seas into cold air and by soaring gulls) show cell sizes varying from a few centimeters across up to several hundred meters.

An intensive study of the superficial surface water of seas and lakes seems justified, in view of the possible correlations between their various states of motion and temperature distribution, and the transfer of heat, momentum and gasses between the air and the water.

The following description of the methods and apparatus used so far will give the reader an idea of the preliminary nature of this first investigation and of some of the problems encountered. Also included is a table of data which shows the common occurrence of thermal instability in surface layers, and some of the conditions under which the surface cooling takes place.

A very sensitive Richter and Wiese mercurial thermometer (see Figs. 34 and 35) was used to measure the surface water temperatures. This thermometer has a bulb 1.5 mm. in outside diameter and 9 cm. long, and it is calibrated in degrees and tenths Centigrade. The small

volume and diameter of the thermometer bulb made it possible to measure temperatures quickly and within small depth ranges. However, it was necessary to stop wave action as much as possible in order to use this instrument satisfactorily. For this purpose a box 60 cm. square with a depth of 30 cm. was used (see Fig. 35). The absence of the bottom in the box allowed free vertical movement to the water inside the box. The grooves in the supporting legs made it possible to adjust the box level so that the edge of the box projecting above the water offered a minimum of interference with the air flowing past and at the same time stopped wave action. Only small waves could be stopped in this way, so it was necessary to work near a windward

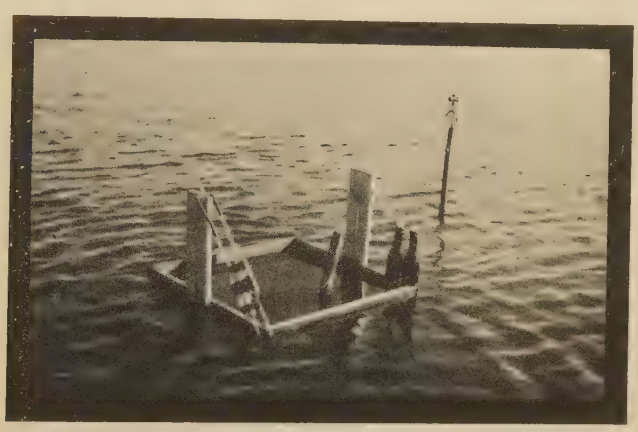

Figure 35. Wave damper in use.

shore (i. e. where the wind came from over nearby land) or during almost calm conditions. The average total depth of the water, where measurements were made, was about 70 cm. and at a distance of from 3 m. to 30 m. from the shore.

Water samples for chlorinity determinations were taken from the surface and at 2 cm. depth with two pipettes lashed together so that their tips were 2 cm. apart vertically (see Fig. 35). The tip of the pipette sampling the surface was ground at an angle so that while drawing in water one could draw in at the same time a stream of air bubbles. This was done to be sure that the pipette tip was held as nearly as possible at the surface. Tests in the laboratory at a vapor pressure difference* of 15 mb., showed that any excessive evaporation

* The saturation pressure of aqueous vapor over the sea water sample at water temperature — the aqueous vapor pressure at the temperature and relative humidity of the air in the laboratory.

due to this procedure was not measurable by the standard Knudsen method of chlorinity determination.

Wet and dry bulb measurements were made with a sling psychrometer; the thermometers of which are calibrated in whole degrees Fahrenheit. The readings were taken at about one meter above the surface of the water. Wind speed measurements were made at a height between 50 cm. and 100 cm. above the water (Fig. 35) with a single Casella anemometer. Correction for anemometer error has been applied to the readings.

Observations were made in a harbor where the salinity was about 30 °/₀₀, in a pond just above high tide level where the salinity was about 3 °/₀₀, and in an inland fresh water pond.

Table 1 shows all measurements tabulated according to increasing difference between the water temperatures at 3 mm. and at 20 mm. The first column gives the number of times temperatures were taken at the two levels (3 mm. and 20 mm.) and the figure in the third column is the average of the differences between these temperatures. Column two indicates whether the readings were made inside or outside of the wave damper. Saturation values of vapor pressure were taken from the Smithsonian Meteorological Tables (1933, table 79). Column four represents the saturation pressure of aqueous vapor at the water temperature at two cm. depth minus the aqueous vapor pressure at the temperature and the relative humidity of the air at one meter above the water. Column six lists the difference between the water temperature at one cm. below the surface and the air temperature at one meter above the surface.

The minimum depth (i. e. 3 mm.) at which temperature observations were made in the water is only roughly correct. In making readings in the surface film, the thermometer was adjusted manually so that there was always a layer of water visibly flowing over the top of the thermometer bulb. It is probable that the depth at which the surface temperatures were made varied from 2 mm. to 4 or 5 mm. depending upon the size of the small surface ripples. The 20 mm. level was determined by marking a centimeter scale on the stem of the thermometer; zero depth being at the level of the bulb of the thermometer.

The lack of a clear correlation between the degree of surface cooling (as expressed in the values in column 3) and the cooling factors measured (columns 4, 5 and 6) is attributed in part to inaccuracies in the depth of the thermometer bulb in making surface film temperature readings; also to unknown factors such as possible variations in the rate of sinking of the cooled water with different wind speeds; differences between the rates of sinking of the cooled water inside and outside of the box; variations in solar radiation; variations in radiation

absorption and emission of the surface water itself; and the possible influence of different amounts of particulate matter in the water on some of these factors.

In the beginning of this work it was thought necessary to make many chlorinity determinations in order to prove that the colder surface film was not also fresher, hence stable. However, when comparable layers of colder water were found on sea water, on brackish water and on fresh water during the same day under approximately the same weather conditions, it was thought unnecessary to continue the chlorinity titrations. Several times, during the observations in salt water, samples were taken as previously described. These samples showed no marked difference between the salinity at the surface and that at 2 cm., though most of the time the surface proved to be slightly more saline. Tests were made with samples drawn from outside the box as well as inside, though of course samples from outside the box could be taken only near a windward shore or during almost calm conditions.

Temperatures taken inside and outside of the wave damping box, when conditions permitted, showed that the cooling of the surface water was not confined to the inside of the box, but was general over the water surface outside as well. The curved lines connecting the "ins" and "outs" in column 2 indicate series of observations which were made inside and outside of the box under otherwise approximately the same conditions. These transitions were made in fresh as well as salt water. It is not suggested here that the wave damping box does not affect the enclosed water, but merely that the cooled surface layer which is measured in it is roughly comparable in depth and degree to the cooled surface layer on the outside, under the indicated weather and other conditions.

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TABLE I

TEMPERATURE READINGS AT 3 MILLIMETERS AND AT 20 MILLIMETERS. OBSERVATIONS ARRANGED IN ORDER OF INCREASING THERMAL INSTABILITY

1	2	3	4	5	6	7	8	9	10
Number of readings	*Inside or outside of box*	*Av. $T_{3\,mm.} - Av. T_{20\,mm.}$ °C*	*Vapor Press. mb.*	*Wind m sec⁻¹*	*$T_W - T_A$*	*Cloudiness 1–4*	*Water*	*Time E.S.T.*	*Date 1940*
15	in	+0.1	0.8	4.7	−0.7	hazy	Salt	1040	Oct. 15
11	out	0.0	3.1	4.7	−1.0[5]	1	Brackish	1150	Oct. 15
27	out	−0.1	1.5	1.3	+0.3[5]	4	Salt	1515	Oct. 8
9	out	−0.2	3.4	4.4	0.1	hazy	Brackish	1455	Oct. 13
22	in	−0.2	4.6	4.2	0.0	2	Salt	1200	Oct. 6
14	in	−0.2	7.0	2.4	2.7	2–3	Salt	1015	Sept. 12
10	in	−0.3	5.4	3.4	0.8	0	Salt	0855	Sept. 28
4	out	−0.3	6.0	5.1	1.8	4	Salt	1540	Oct. 2
8	out	−0.3	13.0	0.7	0.7	0	Fresh	1150	Oct. 14
7	in	−0.3	5.9	3.6	2.7	0	Brackish	0950	Oct. 19
18	in	−0.3	6.0	5.1	1.8	4	Salt	1500	Oct. 2
13	in	−0.3	7.7	4.8	1.0	2	Brackish	1215	Oct. 18
39	in	−0.3	6.2	1.7	0.0	2	Brackish	0900	Sept. 19
10	in	−0.3	9.3	3.2	2.1	1	Salt	1135	Oct. 10
8	out	−0.3	9.3	3.2	2.1	1	Salt	1155	Oct. 10
22	in	−0.3	8.0	2.7	1.1	0	Salt	1105	Sept. 27
13	in	−0.4	13.0	0.7	0.7	0	Fresh	1210	Oct. 14
9	in	−0.4	3.6	4.1	1.1	hazy	Brackish	1620	Oct. 12
5	out	−0.4	13.0	0.7	0.7	0	Fresh	1220	Oct. 14
25	in	−0.4	8.0	2.0	1.7	0	Salt	0920	Sept. 13
8	in	−0.4	6.2	1.8	0.7	1	Salt	0650	Sept. 18
20	in	−0.4	7.3	3.9	1.8	0	Salt	0900	Sept. 27
7	in	−0.5	8.6	4.9	4.9	0	Salt	1115	Oct. 16
7	out	−0.5	8.9	3.3	1.4	4	Salt	1300	Oct. 9
20	in	−0.5	9.6	2.1	0.0	0	Salt	0950	Oct. 14
10	in	−0.5	13.1	1.5	10.0	0	Fresh	1140	Oct. 19
5	in	−0.5	8.9	3.3	1.4	4	Salt	1245	Oct. 9
11	in	−0.6	11.0	2.1	5.9	1	Fresh	1120	Oct. 18
5	out	−0.6	11.0	1.0	13.4	2	Fresh	2310	Oct. 10
7	in	−0.6	9.3	0.8	4.2	1	Fresh	1615	Oct. 10
23	out	−0.6	9.3	0.8	4.2	1	Fr sh	1540	Oct. 10
21	in	−0.7	8.7	2.5	1.8	0	Brackish	0750	Sept. 23
10	in	−0.7	9.0	6.6	3.9	0	Brackish	0940	Sept. 26
12	out	−0.7	13.1	0.9	10.0	0	Fresh	1055	Oct. 19
12	in	−0.7	8.4	3.6	2.9	0	Salt	1025	Oct. 18
1	out	−0.8	12.7	0.8	11.9	0	Fresh	2130	Sept. 29
6	out	−1.0	9.9	0.9	9.7	1	Fresh	2230	Oct. 15

PLANKTON STUDIES. V. REGIONAL SUMMARY

By

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Certain aspects of phytoplankton growth which are so generally recognized as to be practically axiomatic are presented graphically in Figure 36. They are explained as follows:

The plankton crop (A, A') represents the momentary state of the cumulative balance between the results of phytoplankton production (F) and phytoplankton removal, or reduction (I). Phytoplankton production, i. e., the synthesis of new organisms, is dependent on the accumulation of new building stuffs by the plankton association, namely photosynthesis (G, G') and the utilization of nutrients (H). Consumption of nutrients is favored by a high concentration of nutrients in the water (E_1); such utilization automatically reduces the concentration (H_2). The nutrient concentration is replenished by regeneration and vertical transport (L and M); regeneration is dependent on phytoplankton death (I_3). The latter may be a process of natural death due to depletion of energy, as when there is an unfavorable balance between photosynthesis and respiration. This is generally a result of the plant's sinking below the phototrophic zone (K_1). Another important factor in phytoplankton reduction is zooplankton grazing (J).

Temperature probably has a direct effect on all metabolic processes. These include the synthesis of new plankton material (C_1), photosynthesis (C_2, C_3), respiration (C_4), zooplankton activity (C_5), and bacterial metabolism (C_7). Temperature also has a physical effect on the rate of vertical transport (C_8) through its influence on density, and on the sinking rate (C_6) through viscosity and perhaps density, although the latter is less likely to be of primary importance because the sinking diatoms, as well as the sea water, are affected by temperature, so that the change in relative densities is dependent only on the slight differences that exist in their coefficients of thermal expansion.

Light generally has a direct effect on photosynthesis (D_2, D_4), although strong radiation may be inhibitory at the surface (D_3). It also influences zooplankton activity (D_5) and is of course related with temperature (D_1).

In tropical waters and in temperate regions during the summer the effective regeneration, that is, the rate of vertical transport, is influenced by depth (B_3). Moreover, the total crop of phytoplankton is affected by depth when the latter is less than the potential thickness of the phototrophic zone or when bottom influences reduce the trans-

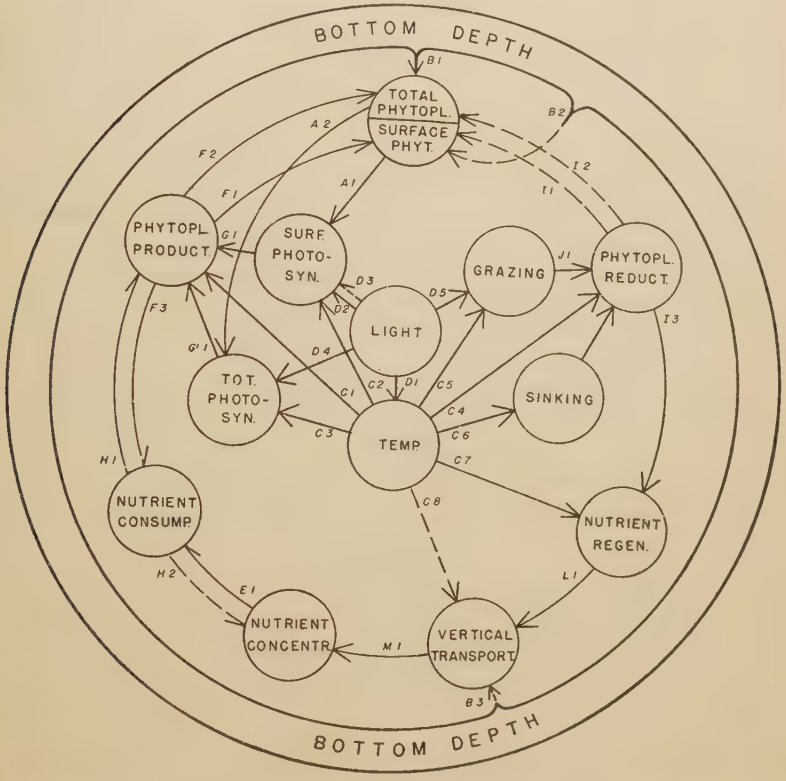

Figure 36. Relationships of plankton and environment. Solid lines indicate direct relations, broken lines inverse ones. See text for further explanation

parency (B_1). On the other hand, depth may be an important factor in reducing the surface concentration of plant material when vertical turbulence carries it to lower levels (B_2).

The size of the plankton crop influences photosynthesis (A_1, A_1'), since the quantity of the catalyst is an essential feature of the reaction; however, this effect may be partially invalidated by the fact that the size of the crop is inversely related with light penetration (A_2').

QUALITATIVE ANALYSIS

The diagram as presented is admittedly far from complete. It is adequate, however, for an introductory analysis of the relationship of the plankton with its environment.

On the basis of the diagram equations may be drawn up by which the value of one term may be expressed by the value of other terms. For example, $A = F_1 - I_1$, or expanding into the indirect relations, $A = G_1 + H_1 - I_1 - J_1 - K_1$. Going still further afield, the plankton may be at least partly expressed in the terms of the simple environmental factors. The relation between temperature and plankton, for example, may be stated as $A = C_1 + C_2 + C_7 - C_4 - C_5 - C_6 - C_8$. In this case the relationship becomes highly indirect, since temperature is acting through several physiological processes as well as upon two physical factors which in turn influence some of these processes. Thus it is evident that the farther we progress into indirect relations, the more complex and vague their expression becomes. Unfortunately, however, in the application of such systems to practical problems the expression cannot be made very simple, for the accurate measurement of physiological processes, such as F to M, is difficult if not impossible, and the simple biological and environmental variables, such as A to E, are generally all that we know of a plankton association. Moreover the degree of relationship of the various factors is such that they seldom have a single, simple effect on the plankton. Thus the qualitative analysis of such diagrams is both difficult and vague.

As an example of such analysis we may begin with nutrients. There is an obvious positive relation between nutrients and phytoplankton (E_1 H_1 F_1), but since the reaction can go in the opposite direction (F_1 F_3 H_2) (the direction of the arrows is of no significance in correlations, which of course test the degree of relationship irrespective of causal principles), it is not possible to predict whether the net correlation between the two variables will be positive or negative. It depends on the relative importance of the two processes. The relation of this part of the diagram to other parts, however, may be tested by introducing a third variable. For example depth has a positive relation with the nutrient-phytoplankton reaction chain through B_1, and a negative relation with nutrients through B_3 M_1. Thus, while we do not know what the correlation between depth and nutrients is, we can predict that the elimination of B_1 would shift the correlation toward the negative side. This can be put to a practical,

TABLE I

QUALITATIVE CLASSIFICATION OF CORRELATIONS

			Temperature	*Light*	*Depth*	*Nutrients*	*Plant Pigments*	*Oxygen Production*
Total Plant Pigments	Group I: Temperature, Light, and Depth	+ Factors	C_1, C_3, C_7	D_4	B_1			
		− Factors	C_4, C_5, C_6, C_8	D_5, A_2' (D_4, G_1', F_3, H_2)	B_3			
	Group II: Temperature, Light, Depth, and Nutrients	+ Factors	C_1, C_3	D_4	B_1	E_1		
		− Factors	C_4, C_5, C_6	D_5, A_2'		(F_3 H_2)		
Surface Plant Pigments	Group I: Temperature, Light, and Depth	+ Factors	C_1, C_2, C_7	D_2, (D_3 G_1 F_3 H_2)				
		− Factors	C_4, C_5, C_6, C_8	D_5, D_3 (D_2 G_1 F_3 H_2)	B_2, B_3			
	Group II: Temperature, Light, Depth, and Nutrients	+ Factors	C_1, C_2	D_2		E_1		
		− Factors	C_4, C_5, C_6	D_5, D_3	B_2	(F_3 H_2)		
	Group III: Temperature, Light, Depth, Nutrients, and Oxygen Production	+ Factors	C_1			E_1		G_1
		− Factors	C_4, C_5, C_6	D_5	B_2	(F_3 H_2)		
Oxygen Production	Group I: Temperature, Light, and Depth	+ Factors	C_2, C_7	D_2				
		− Factors	C_4, C_5, C_6, C_8	D_3 D_5	B_2, B_3			
	Group II: Temperature, Light, Depth, and Nutrients	+ Factors	C_2	D_2		E_1		
		− Factors	C_4, C_5, C_6	D_3 D_5	B_2	(F_3 H_2)		
	Group III: Temperature, Light, Depth, Nutrients, and Plant Pigments	+ Factors	C_2	D_2			A_1	
		− Factors		D_3				

quantitative test because B_1 is statistically eliminated* by deriving the partial correlation of depth and nutrients in respect to phytoplankton.

Further predictions are obtained in Table I, which utilizes this method on a larger and more complex scale. The effects associated with the physical quantities depth, temperature, and light are assigned in the fashion indicated by the diagram to the biological variables total and surface phytoplankton and surface photosynthesis. Nutrients and other factors are then introduced which change the effect of the primary variables in a way that can be predicted according to the diagram.

There are three orders of predictions that can be made from the table. The first order consists of those factors which are simple and direct and to which a positive or negative sign may be assigned definitely. These are as follows: temperature under Group III of the oxygen production correlation; light in Group III of the surface plant pigments; depth in Group II, total plant pigments, and in all groups under surface plant pigments and oxygen production; oxygen production in Group III of surface plant pigments; and plant pigments in Group III under oxygen production. The second order of predictions is concerned with changes in successive groups which, by the elimination of certain factors, cause the correlations to move either in a positive or negative direction. Thus, in the temperature column, between Groups II and III of surface plant pigments, the positive factor C_2 is eliminated, which should cause the correlation to move in a negative direction, and in the oxygen production section the temperature correlation should move in a positive direction between Groups II and III with the elimination of the negative factors C_4 C_5 C_6. In the light column positive changes can be predicted between Groups I and II of the total plant pigments and between Groups II and III of oxygen production. In the depth column the elimination of B_3 causes a positive change between Groups II and III of all three sets of correlations.

The third order of predictions is concerned with the simultaneous removal of positive and negative factors. This is not a strictly valid method, since there is nothing in the diagram itself that permits

* Statistical elimination by partial correlations is, in the mathematical sphere, comparable to the experimental procedure of holding a particular factor constant. In the case under consideration, the partial correlation of depth and nutrients in respect to phytoplankton is equivalent to a simple correlation between depth and nutrients in a series of experiments in which the quantity of plankton is held at a mean level. In either case the phytoplankton may be an important factor, but its variations do not exert any influence on the depth-nutrient relation.

predictions to be made on these grounds. It is considered permissible, however, when, on other logical grounds, one factor is obviously much more important than the other. The case in point is the simultaneous removal of C_7 and C_8 between Groups I and II of all three sets of correlations. C_8 obviously takes precedence over C_7 because the regeneration of nutrients can have no effect on the surface concentration unless vertical transport occurs. It is therefore predicted that the removal of C_7 and C_8 will cause the correlations to move in a positive direction.

QUANTITATIVE ANALYSIS

The practical application of the theory built upon the fundamental assumptions of the diagram is derived by means of regional averages obtained from the four previous papers of this series. They are split up into six groups of data: Stations 1 and 2 at the Dry Tortugas (Riley, 1938) are treated separately, also the southern and northern

TABLE II

Regional Averages

	Surface Oxygen Production Grams/m³/Day	*Surface Plant Pigments Units/m³*	*Total Plant Pigments Thousands of Units/m²*	*Total Depth in Meters*	*Phosphate mg.-Atoms per m² at the Surface*	*Temperature*	*Light G.Cal./cm²/ Day*
Tortugas, Station 1	0.30	1520	31	19	0.057	28.42	450
Tortugas, Station 2	0.13	680	2	3	0.042	28.30	450
Southern Stations, N. Atlantic	0.09	1300	345	2300	0.062	25.15	460
Northern Stations, N. Atlantic	0.18	4100	143	1000	0.163	13.69	460
Long Island Sound	0.47	54800	1096	20	0.918	11.29	300
Georges Bank	0.34	12500	807	185	0.728	8.48	380
Mean	0.25	12498	404	588	0.328	19.22	417
Standard Deviation	0.13	19346	411	842	0.356	8.28	59

TABLE III

Correlations of Variables Listed in Table I

	Surface Plant Pigments	*Depth*	*Phosphate*	*Temperature*	*Light*
Surface Oxygen Production	.8226	−.6353	.8558	−.5972	−.8849
Surface Plant Pigments		−.3432	.8638	−.5878	−.9550
Total Plant Pigments		−.1525	.9611	−.7742	−.9282
Depth			−.3881	.1473	.4512
Phosphate				−.8326	−.9564
Temperature					.6633

stations of the western North Atlantic (1939); the list is completed by the means of the seasonal cycles in Long Island Sound (1941) and on Georges Bank (1941a). These values are shown in Table II and the simple correlations in Table III.

First of all, it is necessary to examine just what these correlations mean. Mathematically, they are simply an expression of the degree of relationship between two sets of numbers. Biologically they represent the sum of the relations between any two variables as indicated by every possible set of arrows connecting them on the diagram. Thus, for example, the correlation between total plant pigments and temperature represents the fairly direct relations emanating from C_1 to C_6; it also represents the more indirect ones C_7, C_8, D_1 (C_1 to C_8), and $C_1\ F_3\ H_2\ E_1\ H_1\ F_1$. The degree to which temperature represents these latter is of course dependent on the degree of relationship of temperature with light and phosphate. It follows that the mathematical procedure of deriving partial correlations, which makes allowance for such inter-relations, will eliminate these puzzling indirections, and the partial correlation of plant pigments in respect to all the other environmental factors will be simply a statement of C_1 to C_6, with C_7 and C_8 partly eliminated (in respect to phosphate).

Therefore in order to test the theory developed in the previous section, partial correlations are calculated which correspond to the groupings given in Table I. These are shown in Table IV.

TABLE IV

Partial Correlations of Physical and Chemical Factors with Total and Surface Plant Pigments and Oxygen Production

		Temperature	*Light*	*Depth*	*Phosphate*	*Plant Pigments*	*Oxygen Production*
Total Plant Pigments	Group I	−.7129	−.9650	.8404			
	II	.9338	−.0514	.9782	.9982		
Surface Plant Pigments	I	.3060	−.9376	.3965			
	II	−.9750	−.9947	.9097	−.9883		
	III	−.9862	−.9947	.9090	−.9868		.9983
Oxygen Production	I	−.1979	−.7622	−.4029			
	II	−.0364	−.2362	−.5862	.0564		
	III	.8890	.9168	−.9962	.9980	.9983	

The first prediction made from the diagram was that the depth-nutrient correlation would be shifted in a negative direction in deriving the partial correlation in respect to plant pigments. This is vindicated in that the correlation changes from −.3881 to −.8848. All

the predictions in regard to total plant pigments are correct. In regard to surface plant pigments there are four exceptions. Temperature between Groups I and II changes in a negative rather than a positive direction, and all the correlations with depth are positive instead of negative. Two exceptions occur in regard to oxygen production. A high negative correlation with depth is obtained in Group III, whereas the effect of depth should have been eliminated entirely, and between Groups I and II the change was negative rather than positive. Out of a total of twenty predictions there are six exceptions, and five of these are in respect to depth. Thus it appears likely that the theoretical treatment of depth is false, or at least incomplete; but there is nothing that would deny the essential correctness of the rest of the diagram.

Aside from theoretical considerations, the correlations are high enough to have considerable empirical value. Equations derived from the correlations for predicting total and surface plant pigments and surface photosynthesis from the primary environmental factors are as follows:

$$TPP = 1567P + 14t + 0.281L + 0.15D - 587 \quad (1)$$

$$SPP = 2.371D - 117200P - 1528t - 862.7L + 438661 \quad (2)$$

$$OP = 0.000065SPP - 0.0002D + 7.69P + 0.0988t + 0.0549L - 27.744 \quad (3)$$

where TPP is thousands of units of plant pigments per m^2, SPP is units of surface plant pigments per m^3, OP is grams of oxygen produced per m^3 per day at the surface, t is temperature, L is g. cal. of solar radiation per cm^2 per day, and D is depth in meters.

The multiple correlation coefficients for these equations range from .9984 to .9992, and the relation between the amounts observed in the water and those calculated from the equations is shown in Table V.

TABLE V

Oxygen Production and Plant Pigments Calculated from Equations (1) to (3)

	Total Plant Pigments		*Surface Plant Pigments*		*Oxygen Production*	
	Observed	*Equation (1)*	*Observed*	*Equation (2)*	*Observed*	*Equation (3)*
Tortugas, Station 1	31	29	1520	380	.30	.30
Tortugas, Station 2	2	1	680	2290	.13	.12
Southern Stations, N. Atlantic	345	345	1300	1580	.09	.10
Northern Stations, N. Atlantic	143	143	4100	4170	.18	.18
Long Island Sound	1096	1097	54800	55040	.47	.46
Georges Bank	807	808	12590	12980	.34	.34

It would be interesting to know how general is the application of these equations. Unfortunately, however, the only other region that can be used for comparison is the English Channel. According to data given by Harvey, Cooper, Lebour, and Russell (1935), the mean temperature at station L_4 during 1934 was about 11.1°, and the surface phosphate was 0.26 mg.-atom. The average solar radiation for the region, estimated from figures given by Kimball (1928) for latitude 52° N., longitude 10° W., is about 222 g. cal. per cm^2 per day. With a depth of 45 m. at L_4, the average total plankton crop according to equation (1) should be about 45000 Harvey units per m^2. Actually the mean annual net plankton crop was about 760 units per m^3 or 34000 units per m^2. Since a fraction of the plankton undoubtedly escaped the net, the result of the calculation does not seem unreasonable.

Theoretically, the equations cannot be expected to apply to any set of data that requires extrapolation—that is, any figures that are beyond the limits of the variables used in setting up the equations. Actually, a small amount of extrapolation may be possible in some cases. It depends on whether or not the regression lines remain linear. In fact extrapolation was employed in the English Channel example, since the value for radiation was lower than in any of the original data. An extreme case, however, the results of which are completely false, is illustrated by an attempt to apply equation (1) to the seasonal cycle on Georges Bank. The calculated and observed values for total plant pigments are shown in Table VI. The most

TABLE VI

Total Plant Pigments on Georges Bank

	Total Plant Pigments	
	Calculated	*Observed*
September	343	560
January	1258	118
March	1319	828
April	931	2303
May	719	871
June	768	478

striking error is in the January results in which the very high calculated value is based on the large concentration of phosphate, which in reality cannot be utilized because light at the low January intensity inhibits growth more strongly than is indicated in the equation. In April the calculated values for plant pigments fall as the phosphate

decreases, whereas the plant pigments actually are going up in accordance with the amount of phosphate present at the beginning of the spring flowering. Special phenomena such as these—nonlinear regressions and lag periods—cannot be expressed by a simple equation. The equations are concerned with longer periods of time which average out special phenomena and leave a residuum of general regional variation, a situation analogous and somewhat more strikingly presented by Deevey (1940), who in a series of Connecticut lakes correlated the summer chlorophyll content of the plankton with the winter nitrate.

With these considerations in mind it is reasonable to suppose that the equations should apply with a fair degree of accuracy to the seasonal averages of any region in which the environmental factors fall within the limits of variation of the original data—namely, temperate and tropical waters. They might apply, though with lesser accuracy, to shorter periods provided the plankton was relatively constant (temperate and perhaps arctic regions during the summer, the tropics throughout most of the year).

Much remains to be done in this field. The equations need to be tested and probably altered to include a larger variety of environments. It might be advantageous to include other factors. The logical treatment of depth as a factor, including as it does several other concepts, remains an enigma. But the results obtained so far indicate that eventually the quantitative aspects of plankton growth can be predicted with considerable accuracy.

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